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PROJECT FLAMBEAU...

An Investigation of Mass Fire (1964-1967)

Final Report - Volume I

by

Clive M. Countryman

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Work Unit 2536-A
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1969

PACIFIC SOUTHWEST
Forest and Range
Experiment Station

FOREST SERVICE
U.S. DEPARTMENT OF AGRICULTURE
P.O. BOX 245, BERKELEY, CALIFORNIA 94701

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arbitrarily selected. The plots, with 25-foot and 115-foot spacing between piles, were built for the selected fire sizes. Fires were started by electrically igniting spitter fuses and squibs.

Instrumentation was developed concurrently with burning of the test fires. It varied greatly in both kind and amount from fire to fire. Emphasis was placed on developing methods of directly and quantitatively measuring parameters of interest. In the "external" approach to study used in the Flambeau program, the parameters of interest were those concerned with the interactions of fire and environment and the changes in energy release rate with time.

The parameters measured in the test fires included (a) air flow in and around the fire area and pressure variations within the fire area; (b) thermal energy production, including mass loss rate of the fuel, temperature in the combustion zone, temperature of gases surrounding the combustion zone, and thermal radiation from the fire area; (c) gas composition, primarily concentrations of carbon monoxide, carbon dioxide, and oxygen within the combustion zone and in the "streets" between fuel beds.

Data collected were not primarily for the purpose of developing statistically valid cause-and-effect relationships. Rather the intent was to gather data which could provide the foundation for development of realistic theory on fire behavior and to provide guides to development of experimental studies, both in the field and in the laboratory. These studies would be aimed at solving fire problems with a reasonable expectation of deriving practical benefits. These objectives were largely accomplished.

Only six test fires were actually burned. And the tests were made under a limited range of fuel and environmental conditions. Data from the tests have yet to undergo rigorous analysis. Nevertheless, it is possible to draw some of the more obvious conclusions from the completed tests. . .

1. Fuel characteristics, including those associated with both fuel elements and fuel beds, are the major controlling factors in fire behavior. The burning fuel provides the basic driving energy for fire behavior phenomena associated with fire. How the potential thermal energy of the fuel is released may be affected in some cases by such environmental conditions as wind speed and air stability. In general, however, the thermal pulse produced by a given fuel bed will depend largely on the characteristics of the fuel and of the fuel bed itself.

2. Rate of thermal energy production is of primary importance in determining fire characteristics and behavior. The rate at which the thermal energy of fuel susceptible to combustion is produced is far more important than the size of the burning area. Close-spaced fuel bed fires in the Flambeau program varied in size by a factor of 11. However, air flow patterns, temperature, fire behavior, and noxious gas production were in general the same in the smallest as in the largest fires. The lower limit of fire size in which mass fire characteristics will appear was not determined with certainty. Because of the major influence of fuel characteristics this limit probably varies with fuel type. In fuels such as were used in Flambeau test fires, mass fire characteristics can be developed in fires in the order of 100,000-150,000 square feet in area. Test results strongly suggest that mass fires can be developed in a smaller area.

3. Strong airflow and turbulence develop within the fire boundaries. In all test fires burned, the strongest air flow and turbulence

SUMMARY

Project Flambeau was an exploratory study into mass fire behavior. The research was conducted by the Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, for the Office of Civil Defense, U.S. Department of the Army, and the Defense Atomic Support Agency, U.S. Department of Defense. The objectives of Project Flambeau were to. . .

- Determine the minimum size of fire and fuel loading at which mass fire, and particularly fire storm effects, occur, so as to provide a "standard" mass fire for future and more sophisticated studies;
- Explore the instrumentation problem in mass fire research, and develop instrumentation for such experimental work;
- Acquire as much quantitative information as possible on fire systems, particularly in those areas of primary interest to civil defense problems,
- Test the validity of the descriptive model of a simple mass fire system.

Six experimental or test fires were burned at isolated sites along the California-Nevada border from 1964 to 1967 (table 1).

Table 1.--Experimental fires burned in Project Flambeau, 1964-1967, California and Nevada

Fire No.	Plot code No.	Date burned	Fuel bed spacing	Arrangement (rows)	Wind	Fuel moisture	Intensity rank[1]
			Ft.	Ft.			
1	760-1-64	1-31-64	115	3 by 3	Moderate	Moderate	3
2	760-2-69	5-15-64	25	6 by 6	Moderate	Dry	1
3	760-3-65	6-11-65	115	3 by 3	Strong	Dry	2
4	460-14-65	12-6-65	25	18 by 18	Light	Wet	6
5	460-7-66	6-14-66	25	15 by 16	Light	Dry	4
6	760-12-67	9-29-67	25	18 by 19	Moderate	Moderate to wet	5

[1]Based on flame height and fire activity in individual fuel beds.

In addition to these six test fires, preliminary fires[1] were burned to study the suitability of available fuels, to check the validity of the "external look" approach to the study of fire behavior, and to gain insight into instrumentation needs of large test fires.

In the six test fires, multiple-fuel beds were used to simulate urban conditions. The fuel beds were built by arranging uprooted pinyon pine and Utah juniper trees in square piles covering about 2,000 square feet. Each pile of fuel was 46.7 feet on a side, averaged 7 feet high, and contained about 40,000 pounds of fuel (dry weight). Test fire sizes of 5, 15, 30, and 50 acres were

[1]Described in 1964 interim report.

of significance is the long time duration of carbon monoxide concentrations within the fire area that are high enough to affect a person's judgment and action, although not directly causing permanent injury or death.

were inside the fire boundaries away from major influence of ambient flow. In the multiple fuel-bed fires the increase in air flow into the fire area was significantly greater than that of ambient flow. Air speeds within the fire area, however, were several times greater than the air inflow at the fire periphery.

4. Radiation is of minor importance in fire spread outside of the fire boundaries. The lack of ignition by radiation outside of the fire boundaries was a marked characteristic of all Flambeau fires in this test series. Radiation as a factor in fire spread can be expected to become important only where spread by flame contact and firebrands is limited. For urban fires, of the type to be expected following nuclear attack, fire-induced turbulence within the area initially ignited will insure maximum flame contact and firebrand movement.

5. For multiple fuel-bed fires the position of a fuel bed in the array has only a minor effect on its thermal pulse pattern. In the mass loss experiment of Test Fire 6, only small differences were found in the mass loss rates for fuel beds in different positions. The differences that did appear seemed more closely related to variation in the circulation pattern within the fire area than to position of the fuel bed with respect to the fire center.

6. The Countryman descriptive model is a realistic portrayal of a stationary mass fire system. All six zones of the model appeared in two of the test fires. In other tests the convection column did not reach heights that permitted smoke fallout and convective development zones to develop. Fire behavior and associated phenomena were generally similar in the fuel, combustion, and transition zones for all fires that produced mass fire characteristics.

7. Wildland fuels may be used to simulate urban fires. Wildland and urban fuel beds are dissimilar and cannot usually be expected to produce similar fires in their natural state. But the thermal pulse produced by a burning fuel bed is dependent so much on fuel bed characteristics that it is possible to select and arrange wildland fuels to produce a thermal pulse that will be similar to that of an urban fuel, and to produce similar fire characteristics. Success in simulation will depend upon knowledge of burning characteristics of wildland fuels and thermal pulse characteristics of the urban fuel bed to be simulated.

8. Fire whirls are a consistent phenomenon in large and intensely burning fires. Fire whirls occurred in nearly all Flambeau test fires, and commonly occur in wildland fires. This phenomenon is of considerable importance in urban mass fire spread and in fire control activity. Fire whirls are likely to be of major importance in civil defense aspects of mass fire because of their destructiveness and their capability to rapidly spread fire and transport noxious gases.

9. Lethal concentrations of noxious gases occur within and adjacent to fires. High concentrations of carbon monoxide, carbon dioxide, and deficiency of oxygen were found in the combustion zone of Flambeau fires. Less severe concentrations appeared between the fires and on the fire edge. Since peak concentration of lethal gases, minimum oxygen, and peak heat occurred at about the same time, their combined effect may be greater than any one alone. Also

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Under EO 850-68

FOREWORD

Subtask 2521E, "Interaction of Mass Fire and Its Environment," sponsored by the Office of Civil Defense, Office of the Secretary of the Army, and by Defense Atomic Support Agency, Department of Defense, was designed to help alleviate the lack of quantitative information on the characteristics and behavior of mass fire. The broad objectives of Project Flambeau were to:

1. Investigate and seek to establish the relationship of the fire spread, fire intensity, and other fire behavior characteristics of mass fire in relation to air mass, fuel, and topography, and to determine the effect of the fire system itself on the environment surrounding it under various synoptic conditions.

2. Investigate tl rate of energy output of fires under various environmental conditions and also the output of noxious gases that might have a bearing on military and civilian action and safety.

Both field and laboratory work were needed to meet these objectives. Because of the need for quantitative information characterizing large and intense fires, work was largely confined to the development of instrumentation and the preparation and burning of field test fires. Size of test fires was scaled upwards as instrumentation and ability to measure such fires were perfected.

The Final Report of Project Flambeau . . . An Investigation of Mass Fire (1964-1967) consists of three volumes: Volume I, comprising this report. Volume II, Catalogue of Project Flambeau Fires, 1964-1967; and Volume III, Appendixes.

Volume I reviews our knowledge of fire behavior and factors affecting it, describes the research approach, instrumentation development, and test fires conducted; and reports results and observations from the test fires completed. Emphasis is given to the work accomplished since the interim report issued in June 1964.

CONTENTS

Mass fires—fires showing the more violent fire behavior—can erupt with savage fury at almost any time. Whether in urban or rural areas, all that is needed is an ignition source and the right combination of fuels and weather. Such fires—raging uncontrolled—can wipe out entire communities, destroy valuable resources, and snuff out many lives.

Experiences in wartime have amply demonstrated that mass fires can threaten entire civilian populations. Even in peacetime, normal ignition sources and natural fuel bodies can create massive conflagrations. With the development of modern weapons, large fires can be ignited with lightning speed and devastating consequences. In either peace or war, man must learn how to cope with mass fire. Civil defense authorities and fire control agencies need to know when mass fires are likely to start and how they are likely to behave.

In 1962, the Forest Service of the United States Department of Agriculture in cooperation with agencies of the United States Department of Defense undertook a large-scale investigation—called Project Flambeau—to add to our knowledge of the characteristics and behavior of mass fire. The study was not designed to develop cause-and-effect relationships, but rather to gain some insight into as many aspects as possible of mass fire. Its broad aim was to investigate mass fire under various fuel and weather conditions, and the interactions of mass fire with its environment.

A series of test fires were burned on isolated sites in California and Nevada. Instrumentation was developed and tested concurrently with these experimental fires. The data collected were intended to provide information about large free-burning fires for use in the development of realistic theoretical and experimental studies aimed at solving specific mass fire problems. The investigation was focused on urban fires and civil defense problems, but information obtained should be useful for other purposes as well.

This volume of the Final Report summarizes the work of Project Flambeau during the period 1964-1967. It outlines our present knowledge of mass fires and suggests some of its characteristics, describes the research approach used, the test fires—including selection of fuel type, fire configuration, and fire size; and development of instrumentation—and discusses the results obtained. And it defines a mass fire and suggests a prescription for an experimental mass fire.

Knowledge of Mass Fires

From their long experience with mass fires, both urban and wildland fire control agencies have contributed a qualitative description of many aspects of fire behavior. Firefighters have developed a remarkable degree of skill in predicting fire behavior, in developing control techniques, and in manipulating fire to attain specified objectives. But much of their knowledge is intuitive—it is not easily converted to the quantitative form needed for generalized application to the problem of mass fire.

The lack of quantitative information has also handicapped theoretical approaches to an understanding of mass fire phenomena. Assumptions have been made about fire phenomena without any assurance that they were valid. Without quantitative data the applicability of theoretical models formulated from such work to the real-life situation must always remain in doubt.

Accumulation of quantitative knowledge of mass fire has been hampered because of the need to limit experimental work to small-scale fires in the open or in the laboratory. Such studies have proved helpful toward an understanding of fire phenomena. They permit careful control and measurement of experimental conditions. And they allow accurate analyses of some basic fire relationships. But the validity of extrapolating from such studies to large, intense fires is questionable.

Some characteristics of large fires have not been observed in small fires. They may not occur, or may be too minute in small fires to detect. It seems likely that a different set of controls on fire behavior may take over after a fire reaches a certain size or intensity. The influence of gravity, lapse rate, and other atmospheric parameters make fire scaling un-

usually difficult. Extrapolation is further complicated by the fact that behavior of fire is a pattern phenomenon, that is, the behavior at one point often depends on the behavior of fire at another point.

Types of Mass Fires

In the past, mass fires have been classified into one of two types: the *conflagration* and the *fire storm.* A conflagration is usually defined as a fire that develops moving "fronts" or "heads" under the influence of wind or topography. And the hot burning area is usually confined to a relatively narrow depth. A fire storm has been defined (Rodden, John, and Laurino 1965) as a fire in which virtually the entire fire area is burning simultaneously. Such a fire is essentially stationary, with little outward spread. It is marked by a towering convection column and inflow of air from all sides. This air inflow is believed to be a major reason for the lack of significant outward spread in fire storms reported during World War II.

A third type of mass fires—the moving fire storm—has generally been overlooked. It is potentially the most dangerous and destructive of all fires. Under certain conditions of fuel, wind, and topography, numerous fire brands can ignite large areas ahead of a moving fire. In such case, the fire can develop many of the characteristics of a fire storm, yet continue to move rapidly into unburned areas. Such fires occur occasionally in wildlands, but generally have not been recognized in urban areas. Because of the very large areas that can be ignited by nuclear attack, moving fire storms can flare up in both urban and wildland areas.

RESEARCH APPROACH

Stationary Mass Fire

The stationary mass fire is the most susceptible to field scale study. Since the fire area is predetermined, those variables concerned with fire spread can largely be eliminated from the experimental design. Location of the fire within the instrumentation network can be accurately fixed. Because there is no fire spread, adequate firebreaks to prevent accidental escape of the fire can be built more readily. For these reasons, coupled with the apparent importance of the fire storm phenomena in civil defense, the experimental program was aimed at the investigation of the stationary mass fire.

It is convenient to consider a fire system as a perturbation within an environmental field. The perturbation is driven by the thermal energy released by the burning fuel. The interaction of the perturbation with the environmental field creates the fire phenomena associated with free-burning fires—the fire behavior. Observations of large and intensely burning fires suggest that a large fire system may have six different zones *(fig. 1)*:

I—Fuel Bed Zone: Extends from the ground to the top of the fuel bed. The vertical dimensions may vary from less than 1 inch to many feet, depending upon the kinds of fuel involved.

II—Combustion Zone: The actively flaming area in and above the fuel zone. Vertical height varies, but is usually less than 100 feet above the fuel bed.

III—Transition (turbulence) Zone: Lies between the combustion zone and the more organized flow of the main convection column. Both upper and lower boundaries are indefinite. In most fires, this zone probably does not extend more than 100 to 200 feet above the combustion zone.

IV—Fire (thermal) Convection Zone: The area between the top of the transition zone and the base of the convection column cap. Energy for the

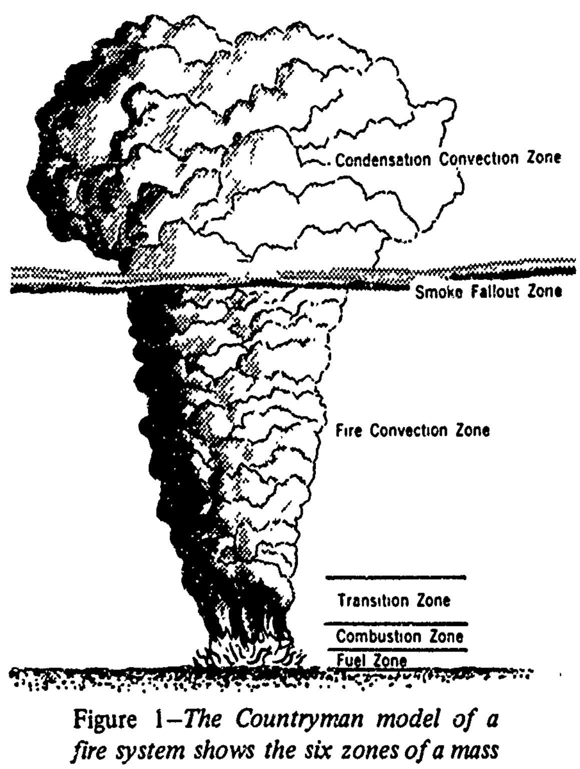

Figure 1—*The Countryman model of a fire system shows the six zones of a mass fire.*

convection in this zone comes chiefly from the fire, although some condensation of water vapor is also likely. Vertical height of this zone may vary from less than 1,000 feet in some fires to more than 15,000 feet in others.

V–Smoke Fallout Zone: A relatively thin zone at the base of the convection cap. This thin layer of smoke spreading out from the convection column is characteristic of towering convection columns.

VI–Condensation Convection Zone: The area from the smoke fallout zone to the top of the convection column. The column usually widens abruptly to form a "cap." It is usually light in color as a result of the condensed water vapor or ice crystals. Heat from condensation is likely the chief source of energy for convection in this zone. This zone is not found in all fires. Its formation depends upon air mass characteristics as well as on size and energy output of the fire. The vertical length of this zone is variable. At times it may approach the length of the fire convection zone.

The total amount of thermal energy released by a fire depends primarily upon the size of the fire and the amount of fuel available for burning. The rate of energy release for the entire fire is a function of fire size and interaction of the combustion zone with the rest of the fire system and its environment. At some critical point in the total energy release rate, mass fire characteristics can be expected to appear. By holding fuel type, fuel loading, and weather pattern constant and by varying fire size, the size at which a mass fire will appear can be determined. The fuel loading and weather constants would, of course, have to be greater than some minimum value below which a mass fire would not develop at any size. Once the size of fire which would produce a mass fire at the given level of fuel loading and weather is determined, then these factors can be varied over the ranges which a mass fire can be developed.

In most theoretical treatments of fire systems, the burning area is considered a simple, uniform heat source. This approach assumes that any areal variations in the energy production pattern will not significantly affect fire behavior. In these theoretical models, fuel-bed configurations of the same size and having the same total rate of energy release will produce the same kind of fire behavior when in the same environmental situation. Any temporal variations in fire behavior would be the result of interactions of the entire fire with its environment and changes in the energy release rate as the fuel is consumed. Parameters of interest would be those concerned with the interactions of fire and environment and the changes in energy release rate with time. Essentially, this approach involves an "external" look at the fire.

In the beginning of the Flambeau program, we recognized that the research would be probing into a largely unknown area for which there was little precedent. Before undertaking full-scale mass fire tests, it was necessary to have quantitative data on the characteristics shown by such fires. This information was needed to test hypotheses suggested by theoretical or mathematical computations, and to insure that instrumentation developed for full-scale tests was both adequate and appropriate. For example, the size of fire needed to produce fire storm effects was uncertain. Some investigators of the fire storms of World War II set the minimum size as greater than 1 square mile. However, observations of wildland fires and prescribed burns (fires set to achieve a desired objective) have indicated that phenomena similar to that ascribed to fire storms often appear in much smaller fires, occasionally in the order of 5 to 10 acres in size. Instrumentation requirements also could not be ascertained since the range of individual parameters and both spatial and temporal sampling requirements were virtually unknown.

Objectives

The investigative program was intended to be exploratory, and to cover a period of about 3 years. At the end of that time we expected that sufficient information would be generated to permit formulation of realistic hypotheses of mass fire behavior and design of sophisticated laboratory and field experiments permitting development of predictive models. At the same time adequate instrumentation systems for full-scale mass fire studies would have been perfected.

During the exploratory and development process we anticipated that data would be collected from test fires that would provide civil defense authorities with general information on conditions within a fire area for immediate use in planning for protection of civilian populations from fire. The information collected in the first phase of the Project would also provide a store of data useful in supplementing and extending that to be collected in more sophisticated studies.

Specific objectives of this program were to:

- Determine the minimum size of fire and fuel loading at which mass fire, and particularly fire storm effects occur, so as to provide a "standard" mass fire for future and more sophisticated studies.

- Explore the instrumentation problem in mass fire research and to develop instrumentation for such experimental work.
- Acquire as much quantitative information as possible on fire systems, particularly in those areas of primary interest to civilian defense problems.
- Test the validity of the descriptive model of a simple mass fire system.

EXPERIMENTAL FIRES

In starting the experimental program, we faced three major decisions: (1) selection of fuel type; (2) selection of fire configuration and sizes; and (3) evaluation of instrumentation needs and development of instrumentation.

The lack of quantitative information required to decide any of these issues, the need to have information that would permit setting up specifications for a fuel bed configuration and size that would produce a mass fire of urban characteristics, and the need to have an adequate instrumentation system for such a fire made it necessary to work on all problems simultaneously.

Selection of Fuel Types

Fuel Parameters

Numerous fuel parameters can affect the inception, growth, and behavior of fires (Byram 1952, 1959). The characteristics of fuel elements known to affect fire include element geometry, surface-to-volume ratio, surface features, moisture content, chemical composition, specific gravity, and thermal conductivity. Important fuel bed characteristics include continuity, arrangement, fuel size distribution, porosity, and amount (fuel loading). All of these fuel parameters and their interactions with the fire and with other environmental factors are important in the understanding of fire behavior. Investigation of effects of these individual characteristics, however, was beyond the scope of the experimental program—that of quantification of a mass fire system. Thus it was desired to limit the number of fuel parameters in the experimental design to a minimum so as to reduce the number of fires needed to accomplish the major objective.

Fuel Sources

Since it is practically impossible to conduct large-scale mass fire tests with in-place urban fuels, simulation of urban fires with other fuels was necessary. Two general kinds of woody fuels were considered.

One of these fuels was scrap lumber from slum and highway right-of-way clearance and sawmill wastes. Although these fuels were not expensive at the source, handling and transportation to an acceptable test area made the on-the-site cost high. They also had the disadvantage of not being consistently available.

The second fuel source was wildland fuels from which test fires could be prepared and burned in the area in which the fuel was found. Preliminary study indicated that wildland fuels would likely provide the most suitable source of material for extensive tests.

Fuel Type Criteria

Wildland fuels in their natural state have a wide variety of characteristics—depending upon species and their growth habits, soil, and other conditions. In selecting a fuel type for fire tests, it was considered essential to meet these criteria:

1. *A large amount of fuel of the selected type should be available:*—Each large-scale fire test requires a great amount of fuel. To keep the fuel variables to a minimum, the fuel selected should be available for all of the contemplated tests.

2. *Arrangement of the fuel into various configurations should be possible at a reasonable cost:*—Wildland fuels do not occur in configurations resembling urban areas and hence must be rearranged to obtain desired configurations and fuel loading.

3. *The fuel type should burn at a rate and with a heat flux output approximating some type of urban fuel bed:*—To permit extrapolation of data obtained in fire tests to actual urban situations, the relationship between burning characteristics of an actual urban fuel and that of the test fuel must be established. If the test fuel characteristics match those of a typical urban fuel, such as a house, then this relationship could be determined and the results directly applied to the urban situation.

4. *The fuel must be found in areas suitable for test fires from a climatic, weather, topographic, and public relations standpoint:*—Large-scale tests depend highly on weather conditions. The tests must be conducted under prescribed weather patterns. Fuels must be burned when dry and hence must have ample "drying weather." Therefore, fire test areas must have a climate and weather pattern that will provide a long

"burning season," and the weather patterns desired for the fire tests must be found reasonably often.

Fuels Available

Three general fuel types appeared to have potential for large-scale fire tests:

1. *California chaparral,* often referred to as "brush," covers extensive areas in the State. Amount of fuel per acre ranges from less than 5 to more than 40 tons (dry weight) (Firestop 1955). It grows over a wide range of climatic zones but chiefly in the warmer, drier areas of the State. Although essential for watershed protection in many areas, chaparral is considered undesirable in many places and is being removed to convert the land to forage or timber production. The fuel dries rapidly and is easy to rearrange with moderate-sized equipment.

2. *Fire-killed timber.* As a result of several severe fire seasons in close succession, a considerable amount of fire-killed timber was available. In the older timber stands, the merchantable trees are removed after a fire. The logging debris and smaller trees are then bulldozed into piles or windrows and burned to prepare the area for reforestation. In young stands where the timber is relatively small, the entire stand is pushed over by bulldozers and bunched for burning. Amount of fuel available may exceed 100 tons per acre. Heavy equipment is usually needed for any fuel rearrangement.

Winter precipitation in the timber zones is relatively heavy, and fuels—particularly those in compact piles—do not become dry enough to burn well for several months after the wet season. Experimental fires there would be limited to a few weeks in the late fall.

3. *Pinyon pine-juniper trees.* Stands of single-leaf Pinyon pine *(Pinus monophylla* Torr. and Frem.*)* and Utah juniper *(Juniperus osteosperme* [Torr.] Little*)* are found in the arid and semi-arid parts of eastern California and over much of the southwest United States, where a long burning season prevails. These two species are usually widespaced, but owing to their heavy branching type of growth there is a considerable amount of fuel in each tree (Storey 1969b). The fuel is highly resinous and burns very well. In most areas the timber is considered to be of no commercial value. Because pinyon pine-juniper stands use much of the little soil moisture available they are being removed in many places to permit better growth of forage. Widely scattered and bulky in form, these plants would require special equipment if they were used in the test fires. The stands that were available had certain drawbacks. They were at high elevation (over 6,000 feet), on generally rocky soil, and far from urban centers where supplies for the test fires and housing for the field crews could be obtained.

Preliminary Fires

Preliminary test fires (Countryman 1964) were conducted to investigate the suitability of each of the available fuels and also to check the validity of the "external look" approach to the study of fire behavior, and to gain insight into instrumentation requirements.

Chaparral Fuels

The first fires consisted of burning chaparral fuels because the supply was plentiful and preparation costs relatively low. Test fires in this fuel were all designed as simple heat sources. Fuels were spread uniformly over the entire area to be burned. Fuel beds ranging up to 92,000 square feet in size and having a fuel loading of about 1.5 pounds per square foot were prepared.

When started by multiple ignitions over the fuel bed area, the fires in the chaparral built up very rapidly. Hot fires resulted, but lasted only a short time because of the small fuel sizes characteristic of the fuel type. Because of the short burning time, convection columns were poorly defined, and air flow patterns did not become stabilized. Heavier fuel loading would probably have increased the burning time to some extent, but would have substantially increased construction costs.

Fire characteristics of chaparral were considered representative only of very light urban construction, and therefore the fuel type was not suitable for studies of stationary mass fire. The fuel type does have potential, however, for investigations of effects of ignition patterns on fire development and for study of the mechanism of fire spread in conflagration-type fires.

Fire-Killed Timber Fuels

Two types of fuel beds in fire-killed timber fuels were tested. Square in shape, the first fuel bed covered about 170,000 square feet. In this fuel bed the timber was felled in place. Most of the trees were less than 8 inches in diameter at the base. Since all fine material had been previously removed by wildfire, the fuel was supplemented with 51 tons of chaparral fuel to permit rapid fire spread from the ignition points and to kindle the tree trunks. The fuel arrangement somewhat resembled that of a residential area leveled by an explosion *(fig. 2).* Fuel loading was 3.5 pounds per square foot, or nearly 600,000 pounds for the fuel bed.

Figure 2–*In fire-killed timber fuel plot, trees averaged about 8 inches in diameter.*

The fuel bed had to be burned under high fuel-moisture conditions. However, the results indicated that this fuel and arrangement could produce a hot fire and a substantial convection column. In addition, the burning time was also long enough for air flow patterns to become established.

The use of fire-killed timber in this manner for test fires had several drawbacks. Supplementing the fuel with fine material proved to be time consuming and expensive. Considerable manual labor was required to collect and distribute the fine fuel. Fuel loading with large fuel was limited to the volume of the timber stand in place. Rearrangement of the fuel into any configuration other than complete cover of the area was nearly impossible because tree stumps impeded the movement of equipment. The tangle of trees and brush made instrumentation of the interior of the fuel bed slow and protection of sensor lead wires difficult. The sharp limb stubs remaining on the trees were hazardous to working personnel. This method of fuel bed preparation was discontinued after one bed was built.

In the alternate method of fuel bed preparation, bulldozers pushed over trees and bunched them into compact piles. The six fuel beds prepared in this manner ranged in size from 7,200 to 49,700 square feet. Fuel loading in the smaller beds ranged from 19 to 25 pounds per square foot. The largest fuel bed held about 40 pounds of fuel per square foot.

Compacted in this way the fuel burned well without replacing the fine material lost in the wildfire. Intense fires lasting for several hours were produced. Fuel beds of similar size within the fuel loading range produced fires that appeared to resemble each other closely. Fire characteristics were analogous to those that might be expected from heavy construction or multi-story buildings.

But considerable difficulty was experienced in

instrumenting the interior of the fires. The long tree lengths and compact piles made it impossible to move any of the fuel to install instrument towers and wiring. Passageways had to be cut into the fuel beds with chain saws to provide access. As the fires burned, the heavy fuel continually shifted about, damaging or destroying sensors, wiring, and instrument supports. This problem was particularly acute in the largest fire and was obviously going to become more difficult as fire size was increased.

The long burning fires would, however, provide ample time to obtain detailed measurements. Because of the long burning time at elevated temperatures and shifting fuel, instrumentation within the fire area would have to be designed to withstand the hostile environment.

Air flow into both chaparral and timber fires was observed to be very slight near the ground (Countryman 1964). In the fire-killed timber fires, it became much stronger in the passageways that had been cut to install instrumentation. This finding suggested that streets and spacing between buildings in an urban mass fire would likely have an important effect on air flow circulation patterns and hence, on fire behavior. If this were true, fuel bed configuration in a fire would have an important bearing on fire behavior and effects. And urban simulation would not be achieved by experimental fires designed as simple heat sources.

An attempt was made to build a test fire with a multiple-fuel bed arrangement simulating urban fuel configuration with the fire-killed timber. It soon became obvious that the cost of large plots would far exceed the resources of the program. Therefore further work in this type of fuel was discontinued.

Pinyon Pine–Juniper Fuels

The tests with fire-killed timber fuels had suggested that multiple-fuel bed fires would be needed to simulate urban conditions. Therefore, pinyon pine and juniper fuels were evaluated for their suitability. Storey (1969b) has reported how trees were selected and sampled at the test sites, the analytical procedures used, and results obtained in relating weight of fuel to size and to dimensions, and in determining distribution of fuel weight. On the basis of the findings, we concluded that . . .

- Dry tree weight, dry crown weight, and dry root weight were closely correlated with maximum crown diameter, average crown diameter, and stem diameter at 1 foot for pinyon pine and with maximum crown diameter and average crown diameter for Utah juniper, which has multiple stems.
- About 25 percent of the total dry weight of small pinyons may be in the needles.
- The fuel size distribution of juniper roots was not determined, but ample data on the total root weight of juniper are available.
- The fuel size distribution curves for the small pinyon and small juniper crowns paralleled one another closely at fuel diameters larger than one-fourth inch.
- Fuel size distribution among branches of identical girth from larger trees of either species appears to vary only slightly.

In a companion report, Storey (1969a) has described in detail the methods used to select the test sites, clear the land, prepare the fuel plots, and determine the amount of fuel. Candidate test sites within the pinyon pine–juniper types were chosen after a reconnaissance survey from a light aircraft, study of aerial photos, and follow-up ground inspection. Two sites were selected: the 45,000-acre Basalt Site north of U.S. Highway 6 and west of Basalt, Nevada; and the 15,000-acre Mono Site south of State Highway 31 along the California-Nevada border and northeast of Lee Vining, California. After the sites were chosen, tree stands were tentatively matched with plot fuel requirements.

Trees in each of the 14 selected areas were lifted, transported, and piled to furnish the fuel for burning. The job of plot preparation was handled by a private contractor. The test fuel beds were built by arranging pinyon pine–juniper trees in piles covering about 2,000 square feet and standing 6 or 7 feet tall. After fuel piles were completed, they were left to dry. Plots were to be burned when their average moisture content approximated that of wood in buildings. Fire built up quickly in the dry fuels, with flames shooting up 50 to 60 feet in less than 5 minutes *(fig. 3)*. After a hot fire had burned for 15 to 20 minutes, it was followed by 60 to 90 minutes of low flames and glowing combustion, but with considerable heat production. The fuel beds required 4 to 6 hours to burn out completely.

In these early trials, we found that the cost of preparing each fuel bed from pinyon pine–juniper trees was cheaper than that of preparing plots from fire-killed timber. And it was only 5 to 10 percent of the estimated cost of preparing fuel beds from lumber.

The manner in which the pinyon pine–juniper fuel burned suggested that it might be used to simulate single-story, wood houses. Data on burning time and heat output from such houses when completely ignited instantaneously were not available. Urban fire chiefs had estimated that a wood house when completely involved in fire would probably burn down in 15 to 30 minutes–about the same time as

Figure 3–*Fire produced in a pinyon pine-juniper fuel bed. This fuel type was selected to simulate an urban residential area in the experimental fires.*

the hot period of pinyon pine–juniper fuel beds. From observations of houses burned in accidental fires it appeared that flame heights seldom exceeded the 50-60 foot flames found in fires of pinyon pine-juniper fuel. The houses, once fully ignited burned in the same general way as beds of pinyon pine-juniper fuel. This fuel appeared to be the best available to accomplish the immediate objectives of Project Flambeau. Therefore, it was decided to use pinyon pine-juniper fuel to simulate an urban residential area in the experimental fires.

Test Fire Design

The selection of the individual fuel-bed dimensions was determined by total fire size, fuel bed spacing, and construction methods available, as well as by area desired and fuel loading. To simulate a moderate-sized suburban house and garage, the fuel bed needed to cover about 2,000 square feet, with a fuel loading of 15 to 20 pounds per square foot (Stanford Research Institute 1954). To keep fuel loading within the desired range and to avoid compaction by heavy equipment fuel beds had to be limited to 7 or 8 feet. Configuration finally selected was a square pile of fuel 46.7 feet on a side, about 7 feet high, and containing 40,000 pounds of fuel (dry weight). This design became the "standard" fuel bed for all fires. The fuel bed was only about half as tall as the usual single-story house. But it could not be made taller and fuel loading maintained without excessive costs for fuel arrangement. This test design can be considered to be adequate representation of single-family suburban houses after exposure to overpressures sufficient to cause structural collapse.

Fire Sizes

To meet the primary objective of determining the size of fire at which mass fire characteristics appear, fire size became the major variable in the experimental program. Test fire sizes of 5, 15, 30, and 50 acres were arbitrarily selected. Since mass fire characteristics have been observed in wildfires and in prescribed burns within this size range, it was expected that the desired type of fire with arranged fuel would also be produced within these fire sizes. If not, enough information would be gained on effects of fire size to permit extrapolation to approximate the minimum size required.

Fuel Bed Spacing

In deciding upon fuel bed spacing several factors had to be considered. Compromises proved necessary. For close-spaced fuel bed plots, we wanted the fuel beds close enough together so that they would probably produce strong interaction effects, yet far enough apart to allow for reasonably free air flow. In wide-spaced plots, we needed enough fuel beds to provide some "central" piles–fuel beds surrounded on all sides by other fuel beds–in the smallest-sized fire.

Previous studies indicated that a 40 percent building density was the upper limit for urban areas, and that 27 percent could be considered the lower limit of firestorm potential (Fed. Civ. Def. Admin. 1957).

Whether a fire convection column should be treated as a thermal plume, as a thermal jet, or perhaps as a combination of both is uncertain. Both thermal plumes and thermal jets can be treated as an inverted cone (Scorer 1958). A plume will have a 1/2 angle of 9 degrees; the 1/2 angle of a jet is 12 degrees. Available pictures of fire convection columns were analyzed for their 1/2 angles. The angles approached (often exceeded) the 12 degrees of the jet. It was decided that the fuel bed spacing in the close-spaced plots should not be greater than would permit merging of the convection columns at about maximum flame height (50 to 60 ft.). If a 12-degree 1/2 angle is used, the distance is about 25 feet, corresponding to a 42 percent building density.

For the wide-spaced plots a spacing of 115 feet allowed nine fuel beds in a square covering about 5 acres–corresponding to a building density slightly under 10 percent–and provided two central fuel beds. Again if a 12-degree, 1/2 angle is used for the convection cone, convergence could be expected at approximately 275 feet above the ground. This difference in spacing of fuel beds and height of convection convergence was estimated to be great enough to produce distinctive and measurable differences in fire behavior.

Plots with 25 and 115-foot spacing were constructed for all selected fire sizes.

Weather Effects

Wind and fuel moisture are the two major weather effects on fire behavior. Wind acts on the fire directly while fuel moisture is affected by relative humidity, temperature, precipitation, and wind. To permit an approximation of these effects the plots of different sizes and spacings were replicated to permit fires under two widely different conditions of wind and fuel moisture. This plan gave a total of 16 plots, about the maximum possible to construct with available funds. One group of plots of all sizes and spacing was to be burned under low wind and low fuel moisture conditions; the remaining plots were to be burned under other combinations of wind and fuel moisture.

Ignition Method

The ignition patterns of fuel in wildland fires influence the rate at which a fire develops and how it behaves. Their effects seem to be due primarily to how fast fire spreads from individual ignition points and spreads throughout the entire fuel bed. If ignition points are far apart, for example, part of the fuel may be burned out before the entire fuel bed is afire. The result is a lower peak energy output rate for the fire area than if the ignition points are close together and fires merge quickly. This same effect can be expected in building fires. A fire in a building ignited at many points will build up more quickly than if it were ignited at a single point. Location of ignition points within the fuel bed may also determine how fast a fire spreads through the entire fuel bed.

Because of natural variations the pinyon pine-juniper fuel beds were not identical in fuel elements of different sizes or in arrangement of fuel elements. To minimize the spread-time factor, it was decided to use an ignition procedure that would spread fire throughout each fuel bed in as short a time as was feasible.

Preliminary work indicated that 1-pound bags of jellied diesel oil fired by spitter fuses and electrical squibs was an excellent ignition device for the fuel being used. Ten of the ignitors near the top of the fuel bed resulted in fire spreading through the entire unit within 30 to 90 seconds. Since the ignitors could be electrically fired, simultaneous ignition over the plot was possible. Later we found that by carefully selecting ignition points, about the same result could be obtained with six ignitors. But fewer than six ignitors, noticeably slowed ignition time.

DEVELOPMENT OF INSTRUMENTATION

At the outset we had anticipated that development of and decisions on instrumentation systems for large experimental fires would be a major problem. This expectation proved to be true. Instrumentation design and testing was carried along concurrently with the burning of fires of different sizes in various fuel types, fuel loading, and fuel bed arrangements. Because of time, manpower, and financial limitations, we decided to concentrate on one phase of instrumentation development and testing at a time. The instrumentation thus varied greatly in both kind and amount from fire to fire. Emphasis was given to development of methods of directly and quantitatively measuring the parameters of interest. However, some methods giving qualitative or semi-qualitative measurements were also explored for feasibility. Whenever possible standard sensors and techniques were used.

Three groups of parameters were considered for investigation: (1) air flow in and around the fire area and pressure variations within the fire area; (2) thermal energy production, including mass loss rate of the fuel, temperature in the combustion zone, temperature of gases surrounding the combustion zone, and thermal radiation from the fire area; (3) gas composition, primarily concentrations of carbon monoxide, carbon dioxide, and oxygen within the combustion zone and in the spaces between fuel beds.

Air Flow Measurements

Descriptions of mass fires and fire storms in World War II and in large urban fires include frequent mention of strong air flow (Bond 1946; Busch 1962). Since air flow appeared likely to be of major importance in quantitative descriptions of mass fire systems early emphasis was given to air flow instrumentation and measurements.

Direct Measurement

In the preliminary test fires, commercially available sensitive cup anemometers were used around the exterior of the fires. Air flow direction was detected by means of wind vanes turning a low torque potentiometer or contact disc. For exterior measurements these sensors performed satisfactorily. This type of air flow instrumentation, however, proved to be inadequate when multiple fuel-bed fires were needed to simulate urban fires, and when internal measurement of air flow patterns within the plot became of prime importance. Most commercial anemometers and wind vanes are constructed of plastic or aluminum. They failed to withstand the high temperatures encountered within a fire area.

Observation of preliminary fires also indicated the presence of strong vertical currents. Since cup anemometers do not indicate true wind speed when the angle of flow from the plane of rotation of the cups exceeds a critical value (MacCready 1966) both the vertical component and angle of flow must be measured.

Adequate anemometers were not available. Therefore, anemometry suitable for use in a hot environment was developed at the Pacific Southwest Forest and Range Experiment Station's Forest Fire Laboratory at Riverside, California. The first anemometer for this purpose was built with exposed parts made of stainless steel. For use within the fire area the body of the anemometer was heavily insulated. Tests indicated that the anemometers would operate satisfactorily in all but the hottest portions of a fire (Murray and Countryman 1968).

Attempts to develop a wind vane for detecting both horizontal and vertical angles and capable of withstanding high temperatures were not successful. It was then decided to measure vertical and horizontal components of air flow with three fan-type anemometers rigidly mounted at right angles to each other *(fig. 4)*. A double ended shaft with fan blades mounted on each end was used to minimize the body effect on anemometer response to air flow from various directions. The anemometers produced good results in three large test fires of multiple-fuel beds.

Response of the anemometers to variation in air speed is linear at all air flow angles *(fig. 5)*. Response to air flow angle deviates somewhat from the ideal cosine curve response *(fig. 6)*, but is close enough to permit correction of speed and angle to good accuracy.

Visual Air Flow Tracers

In the early test fires, air flow near the fire was traced by the use of colored smoke released at ground level. Over short distances this technique was useful for obtaining qualitative descriptions of air flow patterns. The smoke diffused rapidly, however, and air flow streamlines could not be followed far.

Two techniques were tried in an attempt to obtain quantitative data from visual tracers. In one attempt smoke candles were attached to towers outside the fire area and ignited sequentially with electrical squibs. Time-lapse cameras were used to record the

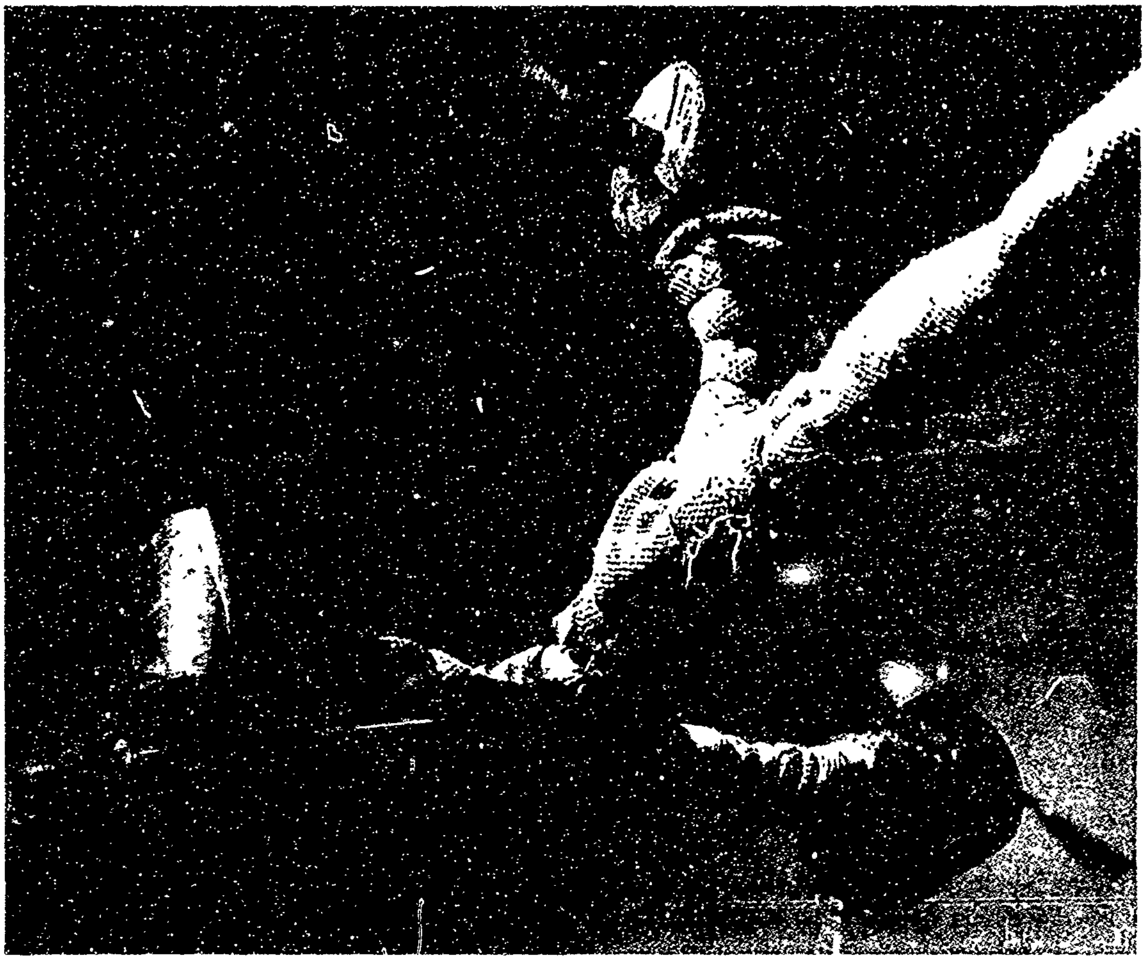

Figure 4—*Vector anemometers measured vertical and horizontal components and the angle of air flow in test fires.*

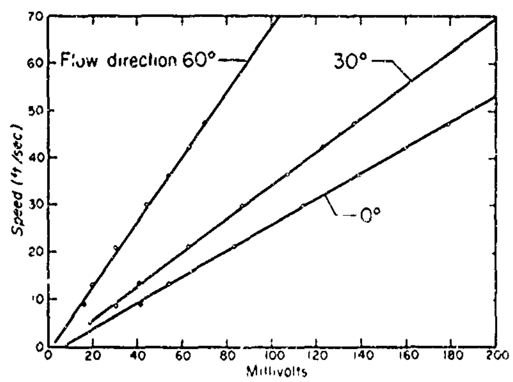

Figure 5—*For all air flow directions, the anemometer responded linearly to changes in air speed.*

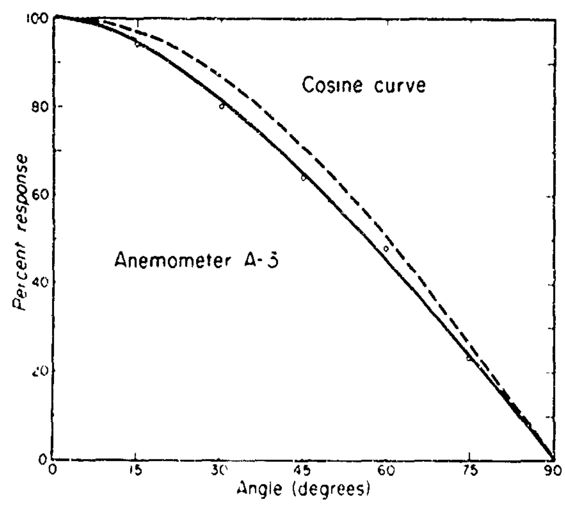

Figure 6—*Comparison of vector anemometer response to ideal cosine response.*

smoke trace. In the second attempt, cold-propellent rockets were equipped with a tracer producing payload. The rockets were fired at a near vertical angle from close to the fire edge. Titanium tetrachloride or aluminum powder was used to produce a visual trace. Both materials left visible traces for 1,000 to 1,500 feet. Again, time-lapse cameras were used to monitor the trace.

The exploratory work with visual air flow tracers showed that this technique would have value in supplementing direct air flow measurement outside the fire area. Diffusion of the tracer material is rapid, however, particularly near the fire edge. High-quality camera and timing equipment are essential. Reduction of information obtained in this manner is also a slow and laborious process. Because of time limitations further work with visual tracers was shelved in favor of development of direct means of air flow measurement.

Pressure Measurements

Three types of pressure sensing instruments were tested. The first type tried was the Kollman absolute pressure pickup (Model 1421-04). This device consisted essentially of a bellows moving a contact over a wire wound resistor. Although the unit worked well in the laboratory, its performance in the field was unsatisfactory. Because of the mechanical linkage the sensors did not respond well to small and fluctuating changes in pressure. Large and rapid fluctuations in pressure, as might occur in a fire whirl, also distorted the linkage, thus affecting the accuracy.

The second type of sensor tested had the barometric element operating a differential transformer. It gave a better signal than the potentiometer type, but did not respond well to very small pressure changes.

The third type of sensor tested was the Wianco differential pressure transducer. It also has a barometric element operating a differential transformer, but was constructed so as to measure differential rather than absolute pressure. This unit required one side of the sensing element to be connected to a chamber of known pressure. The unit performed best of the different types of electrical sensors tested.

On two test fires a liquid manometer was also used as a check on the electrical sensing units. This unit performed well but had to be read manually so that continuous observations were not possible. Because of the long tubes required, some damping effect was very likely present, although readings were nearly identical to those from the electrical units.

Pressure data obtained in the fire tests were generally unsatisfactory. The sensors used in the early fires did not perform adequately. And fire damage to the pressure sensor systems and failure of electronic parts in the recording systems also contributed to poor performance.

Thermal Measurements

Combustion Zone Temperature

In the first tests, temperatures within the combustion zone were measured by chromel-alumel thermocouples made up of 28-gauge wire. These bare-wire thermocouples were mounted on steel masts or strung between masts to get them in the desired position. They did not prove entirely satisfactory. Temperatures within even the smaller fires approached the maximum working temperature (2,500°F.) of the thermocouples. Under prolonged exposure to the elevated temperatures in the fire the bare wires often burned badly and frequently parted under the vibration and strain of the turbulence within the fire.

To solve this problem, chromel-alumel thermocouples sheathed in stainless steel or inconel and with only the junction exposed were obtained. These thermocouple probes proved highly durable and eliminated most of the problems of thermocouple breakage. However, in one very hot fire with multiple fuels, bed temperatures far exceeded the limit of chromel-alumel thermocouples in some parts of the fire (Philpot 1965).

Because very high temperatures were possible in any test fires, it was decided to use platinum-platinum rhodium thermocouples in those area where extreme temperatures were likely. The thermocouples were sheathed entirely in platinum to form a probe. Several new problems arose when these thermocouples were tested in a multiple-fuel bed fire. The thermocouples were very brittle and had to be handled with extreme care. Because of the very low signal output from this type of thermocouple, amplifiers were necessary near the probe installation and within the fire area. Noise suppression in the long signal lines became a major problem since stray signals, possibly generated by the fire itself, were picked up. The probes were much longer (up to 40 feet) than commercially available models, and construction of functioning probes proved to be difficult. Expansion of the metals in the long probes caused some of them to become electrically shorted early in the fire test. The problems of platinum thermocouples were never entirely solved. High quality amplifiers and well-shielded signal lines eliminated much of the noise problem. In future fires using this type of sensor, most of the probe length should be thermally insulated to reduce expansion.

Soil Temperature

Temperatures of the soil at several depths were measured between and under the fuel beds. Moisture-proof thermocouples were installed by digging a short trench 8 to 12 inches from the desired location. A metal rod slightly larger than the thermocouple probe was then inserted horizontally at the required depth level. The rod was withdrawn and the thermocouple probe inserted in the hole and dirt compacted around it. The trench was then backfilled to complete the installation.

Gas Temperature

Since the thermal radiation field in the "streets" between fuel beds in multiple-fuel bed fires is very strong, the use of aspirated thermocouples is necessary to obtain valid temperature measurements. We tried several ways to do this. The first system tested consisted of a simple radiation shield connected to a pipe system. A blower outside the fire area drew air through the shield and past a chromel-alumel thermocouple. Before the air entered the blower unit it was cooled by a water bath to prevent damage to the blower motor and fan. This system worked well, but required considerable time to install—particularly when temperature sampling points were numerous and widespread.

To provide more flexibility, a self-contained aspirated thermocouple unit was designed and built.[1] This unit consisted of small blower, heavily insulated, and enclosed in a stainless steel shell. The thermocouple was mounted in a radiation shield projecting from the bottom of the blower shell *(fig. 7)*. The unit was designed to operate within the fire area for 90 minutes before external heat from the fire and internal heat generated by the blower motor would stop the motor. Although the system provided the desired flexibility, it also had several serious drawbacks. The large amount of insulation made the units rather bulky, and thereby increasing the weight and wind-load on the instrument towers. The rate of heating of the various units varied. And there was considerable uncertainty as to just when the blower stopped during a fire, and hence when gas temperature records were no longer valid. The close proximity of the blower motor to the thermocouple sensor induced noise in the signal lines that was impossible to suppress completely. Because of these disadvantages, this system was abandoned as impractical after two test fires and a more sophisticated aspirated pipe line system developed.

To measure thermal radiation, we used commercially available sensors in all test fires. The type most used was the Beckman-Whitley flat plate radiometer with a 180-degree field of view. This radiometer consists of a thermopile sandwiched between two thin sheets of Bakelite 4 inches square. The plate is exposed to the thermal source in a vertical position. An electrically driven blower directs a stream of air vertically over both sides of the plate to reduce ambient air flow effect and to cool the plate *(fig. 8)*. Since the calibration of the sensor varies with the plate temperature the temperature is monitored by a copper-constantan thermocouple also imbedded in the plate.

Radiometers were exposed outside the fire area at various locations and heights. No difficulties were experienced with the sensors or their installation.

Flat plate radiometers were chosen because of their wide view angle. Tests with narrow view-angle radiometers, such as the Eppley, showed that the small section of the fire viewed did not provide a good measure of the variation and amount of thermal radiation of the fire as a whole. Evaluation of the records from the flat plate radiometer, however, requires pictures of the fire covering the same area viewed by the radiometer so as to provide information on what the radiometer is "looking at."

Mass Loss Rate

In three of the fires, the mass loss of the burning fuel was measured directly to provide a measure of heat output of a fire. In the first two tests, measurement was done by constructing weighing platforms in one corner of selected fuel beds, and loading them with wildland fuel (Countryman 1967a). Weight loss was measured by means of a load cell under each corner of the platform. These platforms had an area of 225 square feet (15 ft. by 15 ft.).

The direct measurement of weight loss proved to be a workable approach from an engineering standpoint. Problems with shifting fuels had indicated that the entire fuel bed rather than a portion of the bed should be weighed. The shifting fuel during burning and rapidly varying wind load also indicated that the load cells should be scanned as nearly simultaneously as possible.

In the third test, five platforms, each 48 ft. by 48 ft., were constructed to replace the standard fuel beds

[1]Philpot, Charles W. *A self-contained aspirated thermocouple.* Pacific SW. Forest & Range Exp. Sta., U.S. Forest Serv., Berkeley, Calif. (n.d.)

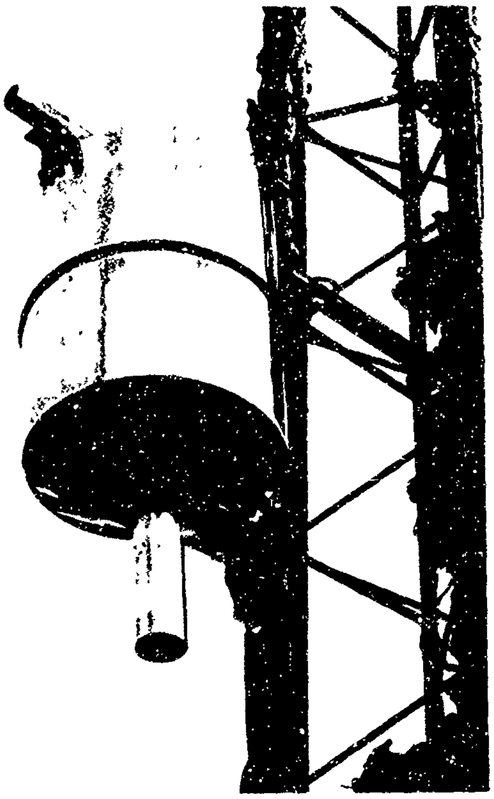

Figure 7—*Self-contained aspirated thermocouple measured gas temperature in the "street" between fuel piles.*

in selected locations.[2] By weighing the entire fuel bed at 10-second intervals many of the problems encountered with the smaller platforms were avoided.

Constant Flow Calorimeter

Visual observations of the multiple-fuel bed fires indicated considerable variation in burning rate of individual fuel beds in the array. Because of their high cost it was not practical to install enough weighing platforms to obtain statistically valid measures of this variation To lower the cost of measuring the variation of heat production and to extend weighing platform data, a constant-flow water calorimeter was designed and tested. The device consisted of a blackened copper tube suspended 10 feet above the fuel bed. Water was pumped through the tube at a constant and monitored rate. Temperature of the incoming and outgoing water was measured at the ends of the tube.

The water calorimeter was tested over one of the weighing platforms in Test Fire 5, on June 14, 1966. The device operated satisfactorily throughout the fire. However, the results of the test indicated that more information on the relation between water temperature difference and burning rates at various stages of combustion would be needed before the data could be satisfactorily interpreted. To provide this additional information water calorimeters were installed over three weighing platforms and two wildland fuel beds in Test Fire 6, burned on September 29, 1967. Unfortunately support failure and lead wire burn-out occurred very early in the fire and little meaningful data were obtained.

Recording System

In the first small test fires, data were recorded on strip chart recorders. For some fires the recording was done at a central point. In other fires, however, it was more expedient to record the data near the sensors, particularly when they were widely spaced. As larger fires were burned and the need for more instrumentation became obvious, centralized recording was adopted for all parameters. The large mass of data

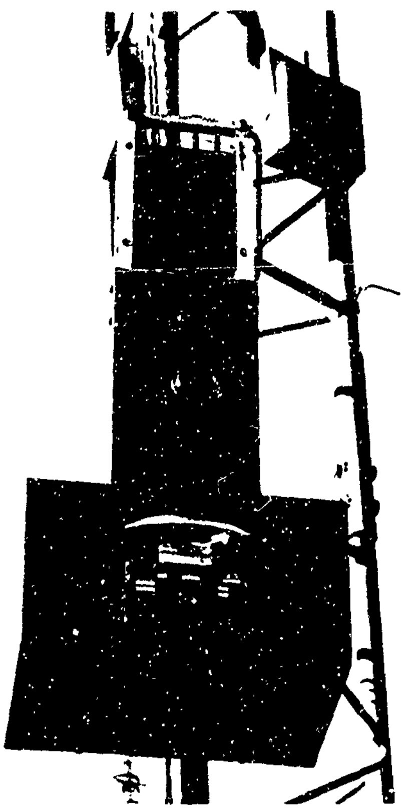

Figure 8—*Flat-plate radiometer measured thermal radiation in the test fires.*

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[2]Murray, John R., and Northcutt, Lee I. *Weighing platforms for large scale mass loss rate experiments in large test fires* Pacific SW Forest & Range Exp Sta., U.S. Forest Serv., Berkeley Calif (n d)

Figure 9—*A trailer housed recording equipment. It could be moved from place to place in the test fire area.*

accumulated during a fire test created a major job of data reduction from strip chart records. A recording system aimed at putting the bulk of the data on punched tape was designed and built so as to permit automatic data processing. Strip charts were still used to record data for which a continuous record was desired since the amount of punched tape equipment available required recording to be done on a time-sharing basis for different sensors and sensor locations. All time-sharing programing was controlled by a master clock permitting time synchronization. The recording equipment was housed in trailers to protect it from weather and dust and to provide mobility *(fig. 9)*.

Large-Fire Instrumentation Systems

The major problem in instrumenting a large experimental fire was the installation of a complete and workable system. Each test plot presented new problems in terrain and soil conditions. Sensor development was proceeding as the program progressed; hence, new and more instrumentation became available in each fire.

Electrical noise in the very long (sometimes more than 2,000 ft.) signal lines caused considerable difficulty. This noise was minimized by using well-shielded signal lines and separating a.c. power line trenches from those holding d.c. signal lines by at least 50 feet. Despite these precautions, however, it was necessary to reserve considerable time before each test for locating and suppressing electrical noise. This work had to be done after all instrumentation was installed since sensor systems that would work well by themselves would sometimes interact with other systems when all systems were activated.

Development of sensors capable of operating in the hot environment proved to be less of a problem than protecting lead wires and sensor supports from intense heat. Insulating materials tended to become weak or brittle and subject to damage and failure from strong air turbulence and flying debris. Backfilling of wire trenches required great care since any burnable material mixed with the backfill could cause wire burnout. In general, most loss of data was from failure of lead wires and instrument supports rather than failure of sensors.

RESULTS AND DISCUSSION

Of the multiple-fuel bed plots prepared, six were instrumented and burned *(table 1)*. From these six fires and from preliminary fires a large mass of data has been collected and extensive qualitative observations made. Palmer (1969) has summarized in catalogue form the data available from the fires. All the planned test fires were not burned; nor have the data been exhaustively examined. But some trends in fire behavior phenomena and fire system characteristics are, nevertheless, evident. Since the number of test fires has been few and were burned under varied conditions, quantitative data were combined with qualitative observations. Under these circumstances, some of the conclusions must be considered speculative. Additional analyses are underway or contemplated in the following subject areas: power spectral density, air flow patterns, correlation fields, mass loss rates, vorticity and convergence patterns.

The development of fires in dry fuels all followed the same general pattern. After being ignited at multiple points the fire spread quickly throughout most of the fuel bed. Fire activity—that is, the vigor of combustion and turbulence in the combustion zone—was slow at first. But as the initial fires merged the build-up in fire activity and flame heights to a peak occurred with startling rapidity. This shift from a relatively slow burning fire to one of high intensity fire sometimes occurred within 10 seconds. Following peak activity flame heights and fire activity then decreased to a relatively low level. This decrease, with the fuels used in test fires, occurred rather quickly but at a much slower rate than the build-up to a peak. After the initial rapid decrease, fire activity continued to dwindle slowly until most or all of the fuel was consumed. In general, the burning pattern of these test fires appears to have followed the idealized energy distribution pattern used by Chandler, Storey, and Tangren (1963) and Lommasson (1965).

Thermal Pulse

Thermal pulse is the rate of heat output per unit area per unit time. Its magnitude and shape are determined by the way in which fuel burns. Thus, all fuel and environmental factors affecting the rate and method of fuel combustion would affect the thermal pulse. A prerequisite to prediction of fire characteristics then, is a knowledge and understanding of how these factors affect the thermal pulse from a fire.

Fuel beds are seldom homogeneous, but consist of a variety of fuel elements. Characteristics of fuel elements known or suspected to be of importance in burning rate of woody fuels include fuel element geometry, surface condition, chemical composition, specific gravity, thermal absorptivity, and moisture content. The kinds of fuel elements making up the fuel bed and the way they are associated with each other affect the rate of burning. Attributes of fuel beds considered of importance are:

- *Continuity* is the gross, horizontal distribution of fuel. Fuels may be spread more or less continuously over an area, may occur only in patches with bare areas in between or may surround bare or nonflammable areas.
- *Arrangement* refers to both the vertical and the horizontal distribution of fuel elements of various characteristics. For example, small or "fine" fuel elements may be uniformly distributed vertically throughout the fuel bed or may only occur at the ground level. Similarly, all fuel particles may be close together or may be far apart.

Table 1–*Experimental fires burned in Project Flambeau, 1964-1967, California and Nevada*

Fire No.	Plot code No.	Date burned	Fuel bed spacing	Arrangement (rows)	Wind	Fuel moisture	Intensity rank[1]
			Ft.				
1	760-1-64	1-31-64	115	3 by 3	Moderate	Moderate	3
2	760-2-69	5-15-64	25	6 by 6	Moderate	Dry	1
3	760-3-65	6-11-65	115	3 by 3	Strong	Dry	2
4	460-14-65	12-6-65	25	18 by 18	Light	Wet	6
5	460-7-66	6-14-66	25	15 by 16	Light	Dry	4
6	760-12-67	9-29-67	25	18 by 19	Moderate	Moderate to wet	5

[1]Based on flame height and fire activity in individual fuel beds.

- *Loading* is the total (dry) weight of fuel per unit of area. This characteristic of fuel beds is probably the most easily measured. It must be considered in conjunction with fuel element and other fuel bed characteristics, however, to be useful in prognosis of burning rates and fire behavior. For example, an area covered with a few widely-spaced logs can have the same total fuel weight as an area covered more uniformly with loosely arranged kindling fuels. Burning characteristics of these two areas would differ widely.

Environmental factors influencing burning characteristics include both air mass and topography. Topography has both a direct and indirect effect.

Slopes modify the heat transfer by radiation, and convection and spread of fire can be quite different—depending on whether the fire is moving up or downslope (Reed 1906; U.S. Forest Service, California Region 1960; U.S. Strategic Bombing Survey 1947). Broken topography and orientation of the topography to windflow also modify fire spread and hence, the thermal pulse pattern as well. In general, fire spread in hilly or mountainous areas can be much faster than on level or rolling terrain for short time periods; over longer time periods, spread rates on less steep terrain may be greater (Chandler, Storey, and Tangren 1963).

Topography affects fire indirectly by affecting local weather and microclimate (Fahnestock 1951; Hayes 1941). The aspect of a slope affects the amount of local heating (Fons, Bruce, and McMasters 1960a) and thus, affects fuel moisture of dead and living fuels. In natural fuels, the variation of heating on slopes of different aspects may also be reflected in the kind and amount of vegetation. Differential heating in mountainous areas has a major effect on local wind patterns and hence, fire (Countryman 1959a, 1959b, Countryman and Schroeder 1959). Channeling of air flow by topography is also an important indirect effect.

The air mass overlying fuels and land is perhaps the most variable of the components of the fire environment. Air mass characteristics recognized as important in fire include wind, humidity, precipitation, temperature, and air stability. Near the surface the air mass is affected by topography and interaction with the fuel. It affects, and may be affected by, the fire system.

In test fires it is difficult to isolate the individual effects of fuel element, fuel bed, and environmental factors on burning rates. Little control of some of the factors is possible in the open, and conditions seldom remain constant for any length of time. The problem is further complicated by the interaction of many of the factors with each other and with the fire system.

The test fires in Project Flambeau were too few to establish definitive relationships, but data collected provide some clues of how fuel and environmental factors can affect the thermal pulse.

Moisture Content

The moisture content of fuel has long been recognized as having a major influence on the ignition, development, and spread of fires (Hawley 1926). Numerous studies have been made of moisture content variations in both urban and wildland fuels (Fielding 1952; Philpot 1963; Pirsko and Fons 1956). This variation can range from less than 1 percent to more than 200 percent for exterior fuels and from less than 10 percent to more than 30 percent for fuels inside buildings.

Moisture in wood fuels reduces heat yield. This reduction may be in the order of 15 percent for a change in moisture from 0 to 100 percent when combustion is complete (Byram 1959). Moisture has an even more pronounced effect on the rate of fire spread. Rothermel and Anderson (1966) burned white pine and ponderosa pine needle beds of varying moisture content in the laboratory. Equations they obtained for rate of spread in still air were:

ponderosa pine = $R_o = 1.04 - 0.044\, M_f$

white pine = $R_o = 1.12 - 0.051\, M_f$

in which R_o = rate of spread (ft./min.)

M_f = moisture content (percent dry weight).

But probably the most important effect of fuel moisture on burning rate is its "smothering" action. Water vapor being distilled from wood dilutes the flammable gases. Evaporation of the water also cools both the fuel surface and the other gases being distilled. All of these effects tend to slow or inhibit combustion and to lower combustion zone temperature.

Observations of wildland fires and prescribed burns indicate that once a fire is established in a fuel bed, the fire will burn well over a wider range of moisture content when the fuel loading is deep than when it is sparse. This probably results from better conservation of available heat in the deep fuel bed, thereby offsetting the effect of the water vapor.

In the relatively dry fuel beds used in most Flambeau tests, fire spread rapidly from the ignition points throughout the entire fuel bed. In dry fuels, the burn-out time of fuel elements of different sizes is selective. Smaller fuels burn first so that as combustion progresses, the residual fuel consists of larger and larger fuel elements. The fuel beds thus tended to

"open up" and also to decrease in height with time.

Test Fire 5 (June 14, 1966) was typical of this burning pattern. Fuel beds in this fire consisted mostly of Utah juniper trees. Fuel elements ranged in size from foliage and small twigs to logs 2 feet in diameter (Countryman 1967b). The thermal pulse produced by this fire *(fig. 10)* closely resembled that of the idealized pulse used by Lommasson (1965) for urban fuels and by Chandler, Storey, and Tangren (1963) for wildland fuels.

The radiation data used in determining the thermal pulse were obtained from a flat plate radiometer placed near the center line of the fire, 200 feet from the lee side of the fire edge, and 10 feet above the ground surface. Based on the total amount of radiation received in the first 60 minutes a radiation index was calculated as a rate in percent per minute. Time period for the rate computation was 6.7 seconds.

Under Chandler's definition (Chandler, Storey, and Tangren 1963), the violent burning period for this fire would be about 18 minutes. This period is defined as the time when radiation (or temperature) exceeds 50 percent of the maximum value recorded. For wildland fuels, this value would fall between the 10 minutes for heavy brush and 24 minutes for timber fuels as prescribed by Chandler. The 18-minute violent burning time would fall between the 13 minutes for heavy residential construction and 25 minutes for commercial construction proposed by Lommasson (1965) for urban fuels.

The fuels for Test Fire 4 (December 6, 1965) were very similar to those in Test Fire 5 (June 6, 1966). However, at the time of Test Fire 4, 3 to 4 inches of snow covered the plot area, and considerable snow lay within the fuel beds. Therefore, the moisture content of the fuel was much higher in 1966, with the small fuels having about 12 percent moisture and the large fuels 24 percent. In Test Fire 5, moisture content was 6 percent for small fuels and 8 percent for large fuels. The snow added more moisture to the fuel, and water vapor to the fire system as it melted.

The burning pattern for Test Fire 4 was entirely different than for Test Fire 5. The fire spread rather slowly from the ignition points and consumed small and intermediate sized fuel elements as it spread. Thus the burn-out of the various fuel elements was not as selective as in Test Fire 5, and some fine fuels were burning in the fuel beds while only the largest fuels remained in the places originally ignited. Flame heights were much lower in Test Fire 4, averaging only about 8 to 12 feet during the most active part of the fire as compared with 30 to 50 feet in Test Fire 5. Consequently, the thermal pulse from Test Fire 4 built up more slowly, did not reach a sharp peak, and remained at a near constant level for a considerable period of time *(fig. 11)*. The violent burning time exceeded the 60 minutes of data used in the analysis. The thermal pulse has the same shape as that which might be expected from a spreading fire in wildland fuels or from a stationary fire in urban fuels, with buildings burning from the top down.

As with Test Fire 5, the radiation index was computed from data obtained with a flat plate radiometer. The radiometer was near the center line of the fire and on the lee side 10 feet above the

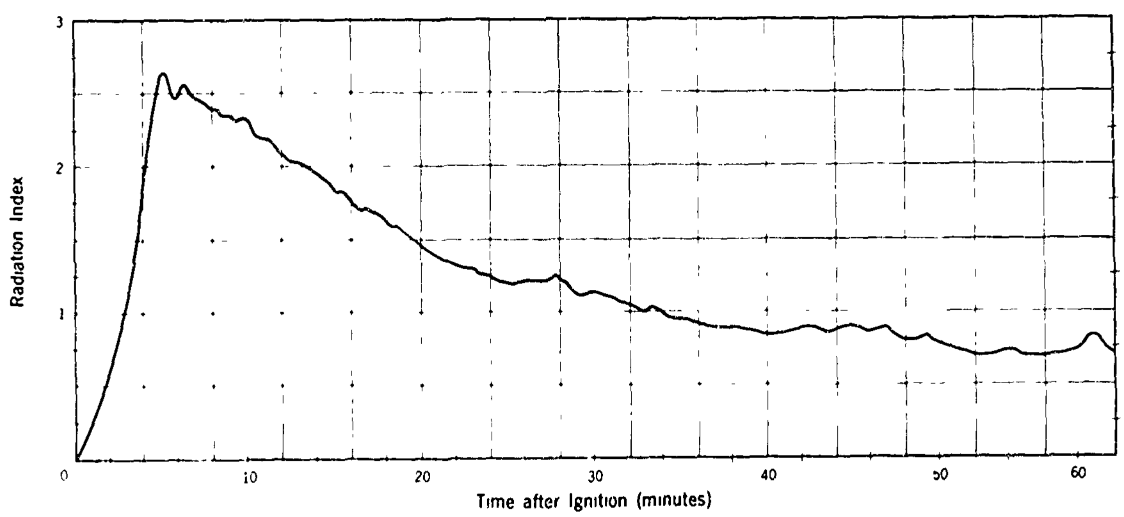


Figure 10–*Radiant thermal pulse from a dry fuel bed with a continuum of fuel sizes, in Test Fire 5, June 14, 1966.*

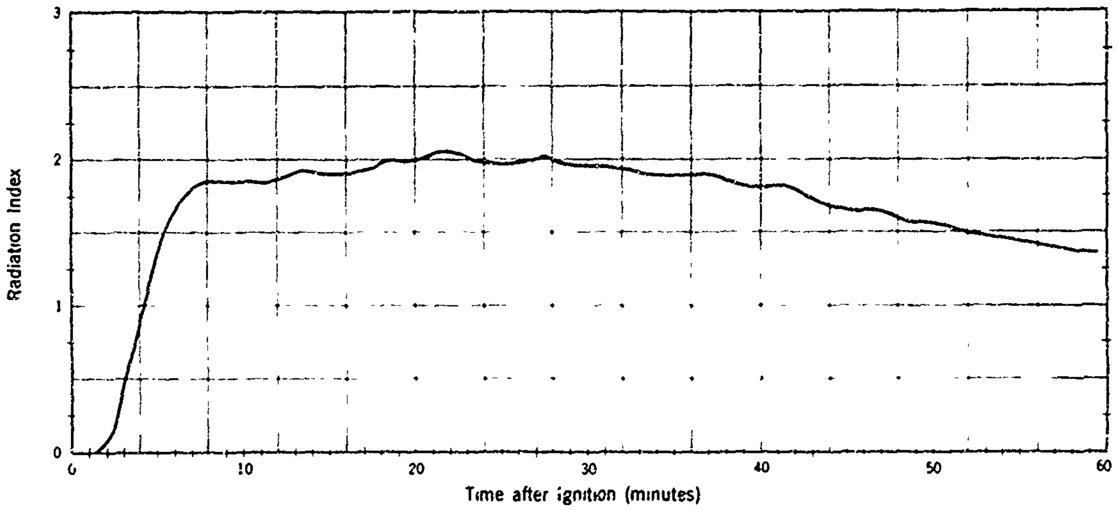


Figure 11–*Radiant thermal pulse from a moist fuel bed with a continuum of fuel sizes, in Test Fire 4, December 6, 1965.*

ground, and 200 feet from the fire edge. Time interval for computation of the radiation index was 15 seconds.

The range in moisture content of Test Fires 4 and 5 did not represent the extreme range possible. Fuels can be much drier than those in Test Fire 5, and fuels arranged like those in these tests will still burn at a higher moisture content than those in Test Fire 4. Different fuel characteristics and arrangements may also increase or decrease the moisture effect.

Fuel Size

For fuel beds with equal loading per unit of area the rate of burning can be expected to increase as the fuel element size decreases, provided there is an adequate oxygen supply. Byram (p. 73, 1959) explains this relationship this way:

> Consider a large pile of dry logs all about 8 inches in diameter. Although somewhat difficult to ignite, the log pile will burn with a hot fire that may last for 2 or 3 hours. The three primary heat-transfer mechanisms are all at work. Radiation and convection heat the surfaces of the logs, but only conduction can transfer heat inside the individual logs. Since conduction is the slowest of the three heat-transfer mechanisms, it limits the rate of burning in this case. Consider now a similar pile of logs that have been split across their diameters twice, or quartered. Assume that the logs are piled in an over-all volume somewhat greater than the first pile, so there will be ample ventilation. This log pile will burn considerably faster than the first one because the burning rate is less dependent on conduction. The surface area was more than doubled by the splitting, so that convection and radiation are correspondingly increased in the preheating effects. The burning surface is also increased by the same amount.
>
> Assume that the splitting action is continued until the logs are in an excelsior state and occupy a volume 30 to 40 times as great as in their original form. Convective and radiative heat transfer will be increased tremendously in the spaces throughout the whole fuel volume, and the rate of burning might be increased to a point where the fuel could be consumed in a few minutes instead of hours.

The ratio, σ, of the fuel surface area to the fuel volume is a convenient way to indicate the relative fineness of the fuel elements in a fuel bed. Fons (1946) and Fons *et al.* (1960b) reported that rate of fire spread is related to σ for small laboratory fires. In investigating the effect of various fuel parameters on ignition time, Fons (19546) found that ignition time decreased with decreasing fuel size (increasing σ).

Fuel bed compactness refers to the closeness of the individual fuel elements in the fuel bed, or how crowded they are together. A highly compact fuel bed has the fuel elements closely packed together; in a low compactness fuel bed the individual elements

are spaced far apart. The converse of compactness is porosity. Thus, a highly compact fuel bed has a low porosity value.

Fuel bed compactness or porosity can be expressed in several ways. Fons (1946) used the ratio, λ, of the volume of voids in the fuel to the surface area of the fuel to measure porosity. He found that rate of spread of small experimental fires varied with the reciprocal of λ, or the fuel bed compactness.

Rothermel and Anderson (1966) found that rate of spread of laboratory fires was correlated with the product of σ and λ. This product, however, is the ratio of fuel bed void volume to the fuel volume—another way of expressing fuel bed porosity.

A convenient way to express compactness is by packing ratio, β or the ratio of fuel volume to fuel bed volume. This ratio has the advantage of being more consistent with the conventional method of expressing density of materials. The reciprocal of β is the fuel bed porosity, γ. The pinyon pine and juniper fuel beds used in Project Flambeau had a porosity estimated to be in the order of 15.

In the Flambeau fires, the effect of fuel size on the thermal pulse can be illustrated by use of the thermal radiation data. As indicated earlier the fuel in Test Fire 5 was made up of a continuum of fuel element sizes from very small to large. This fire produced a thermal pulse that rose quickly to a peak and then began to drop immediately. It reached peak radiation between 4 and 5 minutes after ignition.

In the piled fire-killed timber fires the fuels consisted mainly of large sized-fuels with almost no fuels less than 1 inch in diameter. Preliminary Fire 380-6 burned at low intensity for the first 6 to 7 minutes and then built up very rapidly as fire finally involved all of the fuel. Peak intensity was not reached until about 14 minutes after ignition *(fig. 12)*. The declining portion of the thermal pulse was quite similar to that in Test Fire 5. Violent burning time for Test Fire 380-6 was about 30 minutes. This duration is somewhat longer than the 24 minutes prescribed by Chandler, Storey, and Tangren (1963) for timber fuels, but falls within the 25 minutes for commercial buildings and 55 minutes for city center and massive manufacturing presented by Lommasson (1965).

Another difference between these two fires was the amount of heat production after the first 60 minutes. In Test Fire 5, most of the fuel burned within 90 minutes after ignition, leaving relatively few large pieces still burning. Within 6 hours after ignition, practically all fuel was consumed. In the fire-killed timber a substantial amount of large fuel elements still remained and continued to produce considerable heat for more than 10 hours. It took 25 to 30 hours for the fuels to burn completely.

Radiation data from a fire in piled brush were available. This fuel bed consisted chiefly of fine fuel,

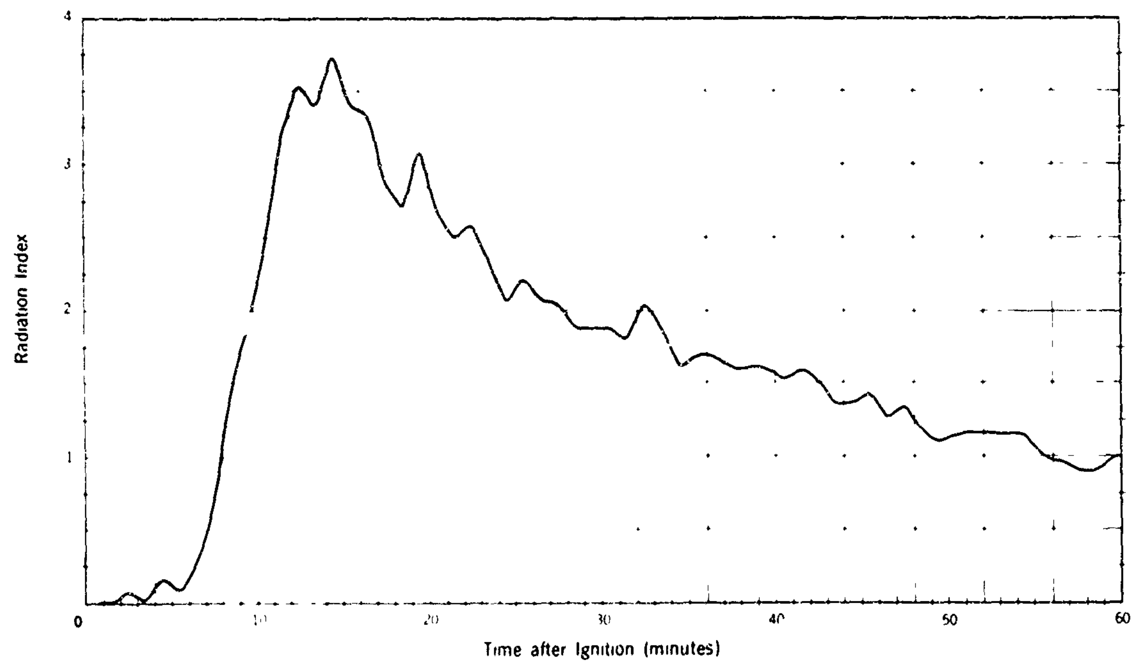


Figure 12–*Radiant thermal pulse from a fuel bed of large fuels, Test Fire 380-6.*

mostly less than 1 inch in diameter. The fire produced a thermal pulse that built up rapidly to a peak in 3 to 4 minutes and then quickly declined *(fig. 13)*. This short, intense thermal pulse appears to be characteristic of fires burning in fine, dry fuels.

Air Flow

Observations of free-burning fires in the open leaves little doubt that surface or low level winds are a major factor in the spread of fire. Many investigations have been made into the effect of wind on fire spread, but there still remains considerable uncertainty of the exact relationships. The uncertainty is even greater for the effect of wind on the burning rate of wood fuels where fire spread is not a factor.

Once ignited a piece of wood appears to go through three phases of combustion. In the initial stage only the surface of the fuel is burning. During this stage, mass loss rates and flaming increase rapidly. In the second stage, char begins to form on the fuel surface, and mass loss rates and flaming become nearly constant. In the third stage, most of the highly volatile material has been consumed.

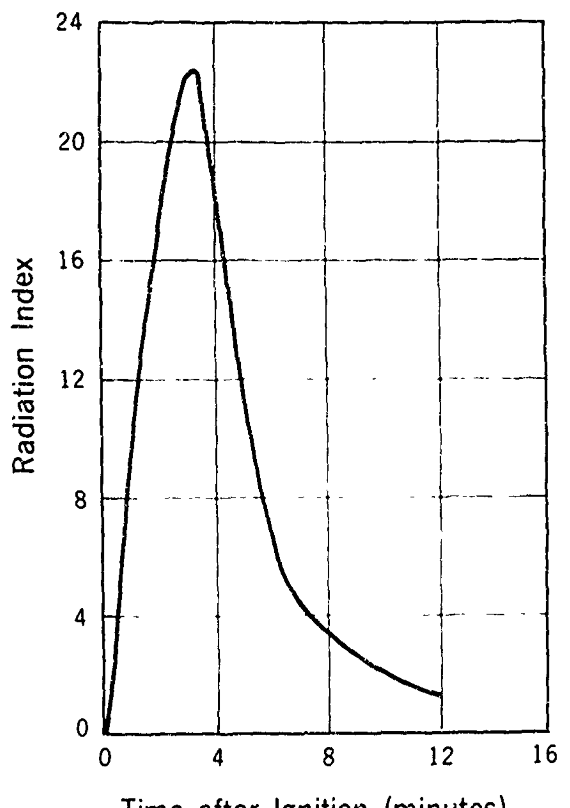


Figure 13–*Radiant thermal pulse from a fuel bed of small fuels.*

Flaming and mass loss rates reach a low level, and glowing combustion predominates until the fuel is consumed or ceases to burn.

Observations of fires in the open suggest that in the initial combustion stage and early part of the second stage, wind does not usually increase the burning rate. Under some conditions it may even slow it down. In the early stages of a fire, the flames fill the voids in the fuel bed, and under light winds, usually extend well above the fuel bed. The flames and fuel restrict the air flow into the fuel bed, and maximum temperatures within the fuel bed can develop. With strong winds the ambient air penetration into the fuel bed is greater, flames may be bent away from the fuel bed, and heat is dissipated rapidly. Thus, strong winds can lower the temperature in the fuel bed and slow the burning rate in the early fire stages.

As combustion proceeds, the smaller fuels and surface of the larger fuels are consumed. The porosity of the fuel bed is thus increased. And cool ambient air can penetrate more readily into the fuel bed interior. If the air flow is not too strong, the wind can have a fanning effect on the glowing char on the fuel surface, increasing its rate of combustion and temperature. This will promote more rapid burning of the remaining fuel than would occur without wind. With strong air flow, however, the fanning effect may be nullified by the cooling action of the ambient air, and the burning rate may be decreased. For any given fuel bed, there is probably an optimum wind speed for most rapid burning. This optimum speed may change as the combustion of the fuel proceeds. In any event, wind exerts its maximum effect in the second and third stages of combustion.

The effect of wind speed can be illustrated by two crib fires burned in the development of a mass loss study for Test Fire 6. Both fires consisted of square cribs of milled lumber. The cribs were 64 inches high and 12 feet on a side. The cribs were identical in construction and held fuel ranging in size from excelsior to material 4 by 4 inches in cross section. Each crib was built on a weighing platform, and as it burned, its weight loss was continuously recorded. Crib A was burned with wind speeds averaging about 13 ft./sec., but with gusts to 22 ft./sec. For Crib B the wind speed was nearly steady at 5 ft./sec. The moisture content of the fuel less than 4 inches in cross section was nearly the same for both cribs, averaging 6.3 percent for Crib A and 6.8 for Crib B. The moisture content of the 4-inch material is uncertain, but was known to be higher in Crib B than in Crib A. However, this moisture difference would

not materially affect the mass loss rate until the last stages of the fire.

Mass loss rates expressed in percent per minute were computed for the time taken to burn 5 percent increments of the fuel to provide a rate comparison at the same stage in combustion for the two cribs. These rates showed that Crib A burned more rapidly throughout the fire than Crib B, with the greatest differences occurring before 50 percent of the fuel was burned *(fig. 14)*. By the time the peak rate was attained in both fires all fuel elements were in or approaching the second and third combustion stages and thus most susceptible to wind effect. If cooling action is not dominant, increasing wind will tend to broaden the peak of the thermal pulse and shorten the burning time for stationary fires.

Thermal Output

Shape and magnitude of the thermal pulse characterizes fire behavior. It follows, therefore, that the characteristics of the fuel bed and fuel element coupled with those of the environment immediately surrounding a fire, are of primary importance in determining the kind of fire and its effect in any fuels subject to burning. The relationships involved are likely to be complex because of the interaction of fuel and environmental factors and the infinite combination of fuels and environment possible.

In dry wood fuels, the peak thermal output is closely related to the burning of the fuel element surface when the fuel bed is ignited near simultaneously. Since combustion depends on oxygen supply, the fuel bed porosity (γ) assumes major significance in describing the thermal output potential of a fuel bed.

With dry fuels and a continuum of fuel element sizes, the thermal peak would occur early in a fire when the fuel bed is ignited almost instantaneously. Where only large fuels are available the thermal peak will be delayed until the entire fuel bed is essentially aflame. Both moisture and wind appear to broaden the thermal pulse peak. With high fuel moisture the thermal peak during the surface burning stage is suppressed by the dilution and cooling of flammable gases by water vapor. And the thermal energy output rate can be expected to be lower at all combustion stages when fuel moisture is high. On the other hand, higher wind speeds broaden the thermal peak by increasing the burning rate when the fuel elements are in the second and third stage of combustion. The potential energy of the fuel will thus be released in shorter time.

Flambeau test fires were burned as stationary fires and ignited in a manner that would minimize the time for spread of fire through the entire fuel bed. Where spread time is significant, or spread is from fuel bed

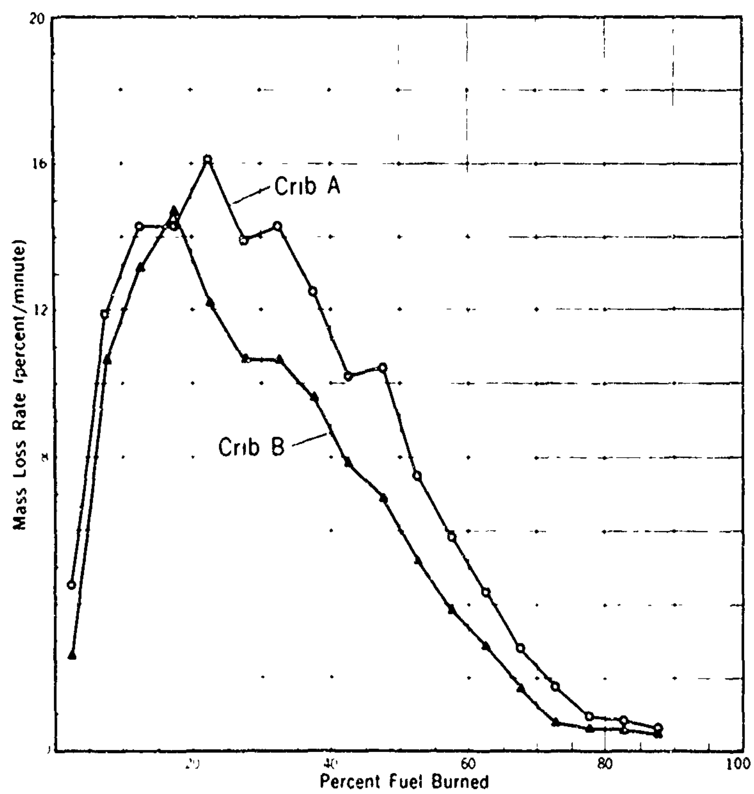


Figure 14—*How wind affected the thermal pulse was demonstrated by an experiment in which two cribs (A and B) were burned under different wind speeds.*

to fuel bed, the thermal pulse from a fire area can assume a variety of shapes and magnitudes– depending upon the manner and rate of spread.

Mass Loss

Quantitative data concerning mass loss rates of fuel in large free-burning fires have been almost completely lacking. The difficulties in directly measuring mass loss rates have forced investigators to use estimates from burning time, thermal radiation measurements, temperature patterns, or ocular estimates.

Direct measurement of mass loss rates in Project Flambeau was first tried in Test Fire 4 (December 12, 1965), when a weighing platform loaded with wildland fuel and supported by load cells was built in one corner of a standard fuel bed. Although some problems were experienced with the instrumentation in this first attempt, the approach appeared feasible and worthy of further effort.

In Test Fire 5 (June 14, 1966) similar platforms with modified instrumentation were constructed in three standard fuel beds (Countryman 1967a). This experiment was designed to explore variations in mass loss rates with position of the fuel bed in the fire area. Although differences in mass loss rates from the three platforms were apparent, probable variations in the wildland fuel bed characteristics made it uncertain whether the mass loss differences were the result of fuel bed position or of fuel bed variations. Problems involved with the use of wildland fuel and placement of the weighing platforms in the standard fuel beds also contributed to difficulties in interpreting the data obtained.

The question of possible variations in mass loss rates with position of the fuel bed in the fire is of primary importance. Information on this effect is needed, not only for the practical application to fire behavior and fire effects prediction, but also in developing scaling laws and establishing criteria for mass fire experiments. And the question is subject to considerable controversy.

Some investigators maintain that burning rates should increase in the interior of the fire and with fire size because of increased thermal interactions and convective activity in large fires. Small laboratory fires tend to support this hypothesis. But other investigators contend that burning rates will decrease in the interior of fires and with increase of fire size because of oxygen deficiencies.

Mass Loss Experiment

To provide some answers to this problem the chief effort in Test Fire 6 (September 29, 1967) was to determine mass loss rates of fuel beds in various positions within the fire area. Profiting from the experience gained with weighing platforms in previous fires, we redesigned both the platform and the instrumentation.[3] Five wildland fuel beds within the array were removed, and five platforms large enough to accommodate a fuel bed of standard dimensions were constructed in their place *(fig. 15)*. To eliminate the variable fuel bed problem, milled lumber was used for fuel platforms 1, 2, 3, and 4 in the fire. Platform 5 was loaded with wildland fuel to provide comparison with the milled fuel beds.

To maximize interaction of thermal effects, the milled fuel beds were designed so that their thermal pulse peak would occur at about the same time as expected for the wildland fuel beds (3 to 5 minutes), and so that most of the milled fuel would burn while the surrounding wildland fuels were still actively flaming. Because of the fuel element differences and a more efficient arrangement of the fuel in the milled fuel beds, it was not expected that the magnitude of the loss rates would be the same as for the wildland fuels. To aid in the design of the milled fuel beds, small cribs of fuel were burned in the laboratory to obtain approximate mass loss rates for different sizes of fuels. Small cribs of mixed fuel sizes were also burned to obtain some insight into the effect of fuel mixtures on the thermal pulse pattern.

The selected fuel bed design contained material ranging in size from excelsior to 4- by 4-inch lumber. Size of material and proportions of each used are given in table 2.

Table 2–*Dimensions and amount of material in milled fuel beds, Test Fire 6, September 29, 1967*

Cross section (inches)	Length	Amount
	Feet	*Percent*
4 by 4	3	42.4
2 by 2	6	19.5
1.5 by 1.5	6	11.9
1 by 1	6	16.8
0.5 by 0.5	6	6.6
Excelsior	–	2.8

The fuel beds were constructed in modules 6 feet square. Each module contained a crib of 4-inch by 4-inch by 3-foot material in its center. The other lumber was nailed together in the form of lattices

[3]Murray, John R., and Northcutt, Lee I. *Weighing platforms for large scale mass loss rate experiments in large test fires.* Pacific SW. Forest & Range Exp. Sta., U.S. Forest Serv., Berkeley, Calif. (n.d.)

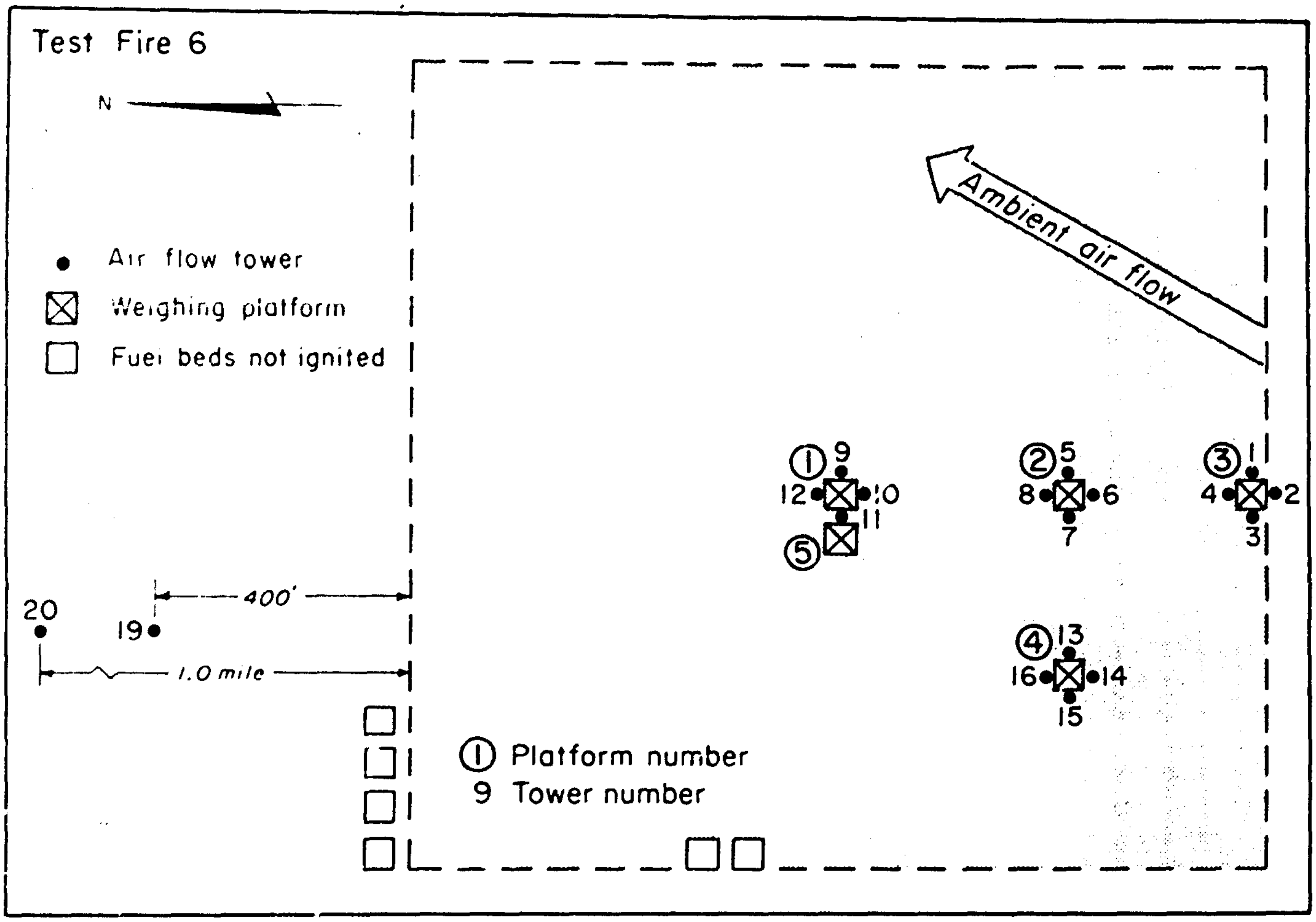


Figure 15--*Weighing platforms and instrument towers were set up in Test Fire 6, burned on September 29, 1967, to determine mass loss rates of fuel beds in different positions.*

6-feet square. These were placed horizontally between each layer of 4-inch material. Excelsior was spread over every other lattice as the module was built.

The first module was constructed using two 4- by 4-inch pieces per layer. making a crib 6 feet tall. This module was burned to test the design. The results indicated more heavy fuel was needed near the bottom of the crib to maintain good burning of the large material. The height of the crib was reduced by 8 inches and the four large fuel pieces removed from the top were included in layers near the bottom. The lattice design was also changed so as to include the material formerly used in the two top units. In the final design each fuel bed contained 49 of the 6-foot square modules *(fig. 16)* and about 30,000 pounds (dry weight) of fuel.

Each fuel bed was ignited by six electrically fired bags of napalm. Weight loss data were recorded at 10-second intervals throughout the test fire.

A full size fuel bed (6A) was burned to test the design and the ignition technique. The mass loss rate curve *(fig. 17)* had the same form as the radiation rate curves obtained for Test Fire 5. The peak loss rate occurred between 3 and 4 minutes after ignition, about the same as estimated for Test Fires 1 (January 31, 1964), 2 (May 15, 1964), and 3 (June 11, 196[illegible]). Flame heights and other fire characteristics were also very similar to that obtained in Test Fire 2—the most intense fire burned in the Flambeau program.

Data Analysis

Large weight loss platforms, such as were used in this experiment, react to wind load and possibly also to pressure changes, although the cavity below the platform was vented as much as it was considered safe to do so during the fire. These reactions result in short-term fluctuations in apparent mass loss rates that are frequently revealed in the 10-second scanning period. The fluctuations were variable but were

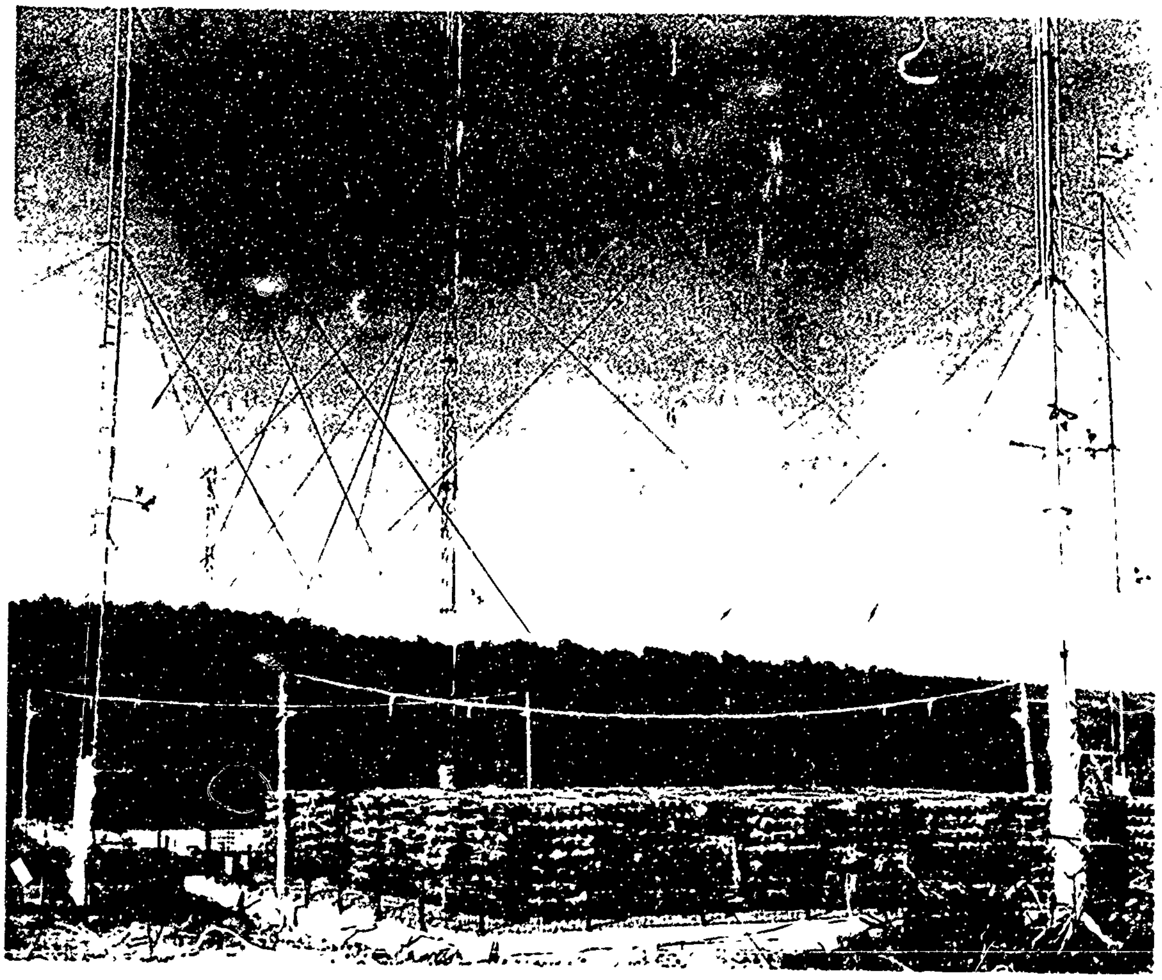


Figure 16–*Final design of milled fuel bed used in Test Fire 6, burned on September 29, 1967.*

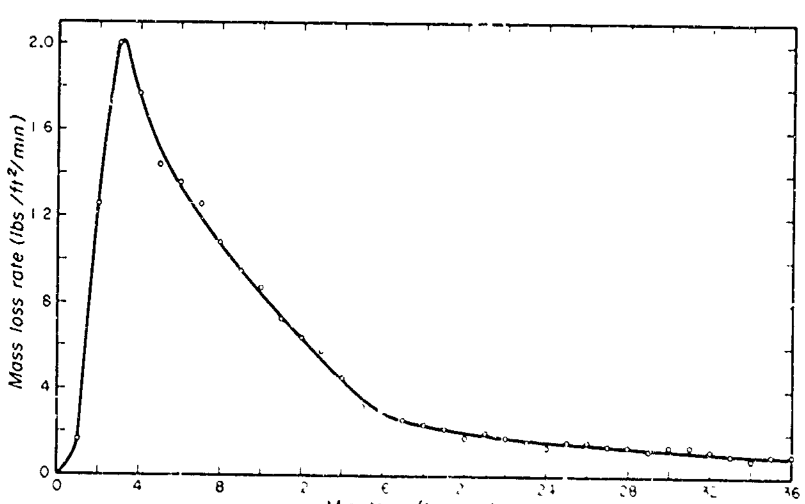


Figure 17–*Mass loss rates for milled fuel crib 6A, burned to test crib design and ignition technique.*

largest (in order of 0.4 lbs./ft.^{2}) in the early part of the fire when it is most turbulent. As the fire progresses, they decline in frequency and magnitude.

For the weighed fuel beds in Test Fire 6 the cumulative percent of weight lost by 10-second periods was plotted over time. A curve ocularly fitted to these points maintained major changes in loss rates, but smoothed out short term fluctuations. The time required to burn cumulative 5 percent increments of the fuel was then determined from this curve *(table 3)*. The analysis was terminated at the 90 percent level since mass loss rates had become minute and data fluctuations made determination of exact times uncertain.

Among the milled fuel beds the difference in time required to burn a given percentage of the original fuel weight was small. Active flaming in these fuel beds was found to subside rapidly after 60 percent of the fuel had been consumed. Maximum time difference among the four fuel beds to reach this level was only 12 seconds. Thus the position of a fuel bed within a fire area does not appear to affect mass loss rates.

The weighed wildland fuel bed burned much more slowly than the milled fuel beds. This finding was not unexpected since the wildland fuels contained a considerable amount of fuel larger than the 4-inch maximum of the milled fuel beds. And part of the finer fuel was lost in shifting the fuel to build the platform and in loading it on the platform. It is possible that the wildland fuel on the weighing platform burned somewhat more slowly than the undisturbed fuel beds.

Table 3 - *Time to burn a constant percent of fuel, by fuel bed*

Loss less (percent)	Fuel bed number . . .				
	1	2	3	4	5
	Minutes				
5	2.4	2.0	2.4	2.3	3.6
10	3.2	2.7	3.0	2.9	4.6
15	3.8	3.4	3.6	3.5	5.8
20	4.5	4.1	4.3	4.2	6.9
25	5.1	4.8	5.0	4.9	8.2
30	5.8	5.6	5.7	5.7	9.9
35	6.6	6.4	6.5	6.5	12.3
40	7.4	7.2	7.3	7.3	15.1
45	8.3	8.1	8.3	8.3	18.8
50	9.3	9.2	9.3	9.4	22.6
55	10.5	10.4	10.5	10.5	27.8
60	12.0	11.8	12.0	11.9	34.2
65	13.8	13.7	13.8	13.6	43.2
70	16.0	16.1	16.0	16.1	52.6
75	19.4	19.3	19.3	19.3	66.8
80	23.9	24.5	24.3	24.5	84.2
85	30.4	31.4	30.6	31.6	103.6
90	40.2	41.8	40.4	43.1	132.6

Although the time required to burn a given amount of fuel did not differ greatly between the four fuel beds in the large fire, the data suggested possible differences between mass loss rate patterns. Mass loss rates, expressed in percent per minute, were computed for the time required to burn 5 percent increments of the fuel. These rates were plotted over the cumulative percent of fuel burned to provide a comparison of mass loss rates at the same stage in fuel bed combustion. The results were:

Fuel bed 3 had the highest peak mass loss rate at 8.5 percent per minute when 10 percent of the fuel had burned. From this peak the rates declined slowly to about 0.4 percent per minute at the level of 90 percent fuel consumption *(fig. 18)*.

The peak mass loss rate for fuel bed 4 was also reached when 10 percent of the fuel had burned. The peak rate for this fuel bed was not quite as great (8.1 percent/min.) as for fuel bed 3. And the mass loss rates declined at a slower rate *(fig. 18)*.

Both fuel bed 1 and 4 had the same peak rate. And it occurred at the same point in fuel consumption. However, after an initial drop in rate from the peak the mass loss rates declined very slowly until after 40 percent of the fuel had burned *(fig. 18)*.

The mass loss rate pattern for fuel bed 2 was unique. Its peak rate was lower (7.8 percent/min.) and was not reached until 20 percent of the fuel had been burned. Although the rate declined slowly, it remained higher than the rates of other fuel beds until 50 percent of the fuel had been burned *(fig. 18)*.

Wind speed and air turbulence are believed to be largely responsible for the differences in the mass loss rate patterns for the milled fuel beds. Anemometer towers were erected on all four sides of each fuel bed. Average wind speeds at the 20 foot level for 2 minutes to 6 minutes after ignition—the time period when mass loss differences were greatest—ranged from 6 to 40 ft./sec.*(table 4)*. The ambient air flow

Table 4—*Average wind speed around milled fuel beds, Test Fire 6, burned September 29, 1967*

Fuel bed No.	N	E	W	S
	Speed (ft./sec.)			
1	40	26	29	25
2	29	31	31	25
3	[1]26	6	16	12
4	15	[2]21	21	24

[1]Anemometer failed 3 minutes and 50 seconds after ignition.

[2]Anemometer failed 5 minutes after ignition.

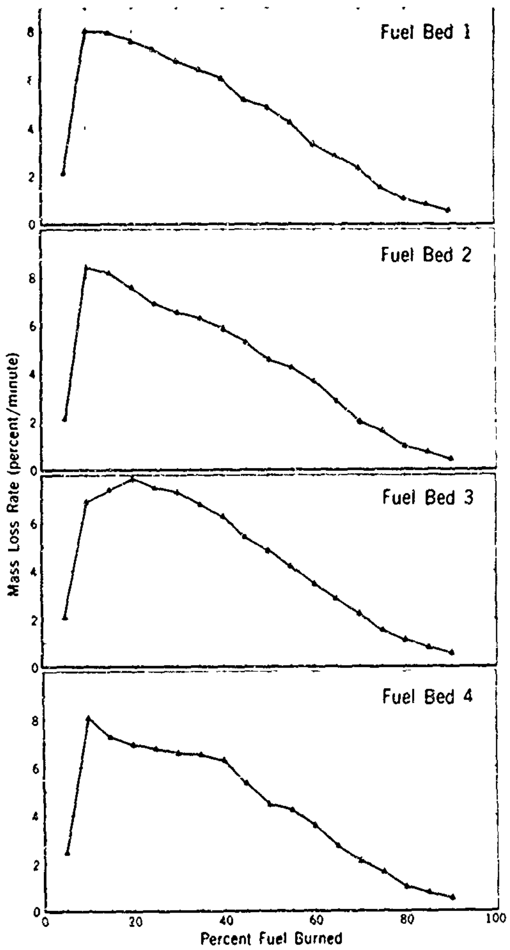


Figure 18–*Mass loss rates for fuel beds 1, 2, 3, and 4 in Test Fire 6, September 29, 1967.*

was generally from the southwest, and horizontal flow direction within the fire boundaries was predominately from the south or west quadrants. Thus air flow data from the south and west towers would be indicative of which flow had the most effect on the fuel bed.

The wind speed at fuel bed 3 was the lowest of the four positions except at the north anemometer tower. The ambient wind coupled with the fire induced indraft forced the convection column and flames from this fuel bed to lean strongly inward. Thus most of the flames from fuel bed 3 were in and above the space between it and the adjacent wildland fuel bed on the upwind side. Hence, the north tower was in the active combustion zone, and the high wind speeds recorded are the result of this position.

The highest average speed for this time period was at the north tower of fuel bed 1, where a fire whirl likely formed nearby between 2 and 2.5 minutes after ignition. A speed of 93 ft./sec. was recorded there at 2 minutes and 20 seconds.

Fuel bed 3, which had the lowest wind speed, gave the highest initial mass loss rate peak. At fuel bed 4 the wind speeds were higher and the mass loss rate peak lower, and the rate declined less rapidly than at fuel bed 3. For fuel bed 1 with still higher wind speeds the sharp initial peak was followed by a period of very slowly declining rates. The air speed around fuel bed 2 was the highest, for the fuel bed as a whole, of any of the four fuel beds. The mass loss record from this platform also had the greatest short term fluctuations, indicating a correspondingly high fluctuation in air flow around the fuel bed. This high wind speed and turbulence delayed the mass loss peak, but gave a longer period of relatively high mass loss rates.

The mass loss rate patterns for the milled fuel beds give strong indication that pattern variations are largely due to air flow. Inside the fire area air flow is extremely variable, with local wind speeds several times that of the ambient flow. Examination of wind and mass loss records indicates that the air flow around milled fuel bed 2 was probably the most turbulent of the areas for which records are available. Momentary wind speeds up to 72 ft./sec. were recorded at low levels in this area.

As indicated earlier, wind appears to increase the burning rate for wood fuels in the second and third combustion stages, and may possibly suppress rates in the initial stage. This relationship seems to be borne out by the mass loss rate patterns for the milled fuel beds.

Results of the experiment suggest that variations in air flow patterns will have more effect on mass loss rates of fuel beds within a fire area than by position with respect to the fire center. Since increase in air flow and turbulence can be expected to be closely related to the rate of heat production, the burning characteristics of a fuel bed are of primary importance. Fuel beds with a low surface-to-volume (σ) are likely to be more strongly affected than those with a higher σ value for the same volume of heat production. Fuel bed spacing and "street" configuration can also be expected to be of major importance.

Air Flow

Strong inflowing winds have often been suggested as one of the characteristics of mass fire. Narrative accounts of urban and wildland conflagrations also often mention high wind speeds in the vicinity of a large fire. Usually these winds have been assumed to be indrafts flowing into the fire, replacing heated air

and gases rising in the convection column.

That such air flow is always into the base of the fire is by no means certain. Instances of wind blowing outward from a fire have been documented (Chandler, Storey, and Tangren 1963; Countryman and Schroeder 1958; U.S. Army Corps of Engineers 1958). This phenomenon has been observed by the author on several large wildland fires. And it has also been reported by others. In addition, there is some evidence (Schroeder and Countryman 1957) that major air entrainment into the convection column may take place well above the ground level. Qualitative observations on many wildfires have indicated only light indrafts into the base of the fire.

In preliminary single-fuel-bed fires, we noted that indrafts directly into the base of the fire were very light, and generally could be detected only with smoke tracers or no-lift balloons (Countryman 1965). In the fuel and combustion zones, these fires appeared to block ambient air movement. Air flow was similar to fluid flow around a solid object, with eddies and turbulence forming in the lee or wake of the fire *(fig. 19)*. Above the fire in the transition and convection zones, the ambient air flow appeared to be absorbed into the fire system.

In wide-spaced, multiple-fuel-bed fires (Test Fires 1 [January 1, 1964] and 3 [June 11, 1965]) it was apparent that individual fires blocked ambient air flow. The fire as a whole also appeared to have a weak blocking effect. The most notable effects, however, was the acceleration of air flow within the fire area and the turbulence that developed (Countryman 1965). Some of this acceleration was probably caused by vertical air currents, but this effect could not be measured since only horizontal flow anemometry was available.

In the close-spaced fuel-bed fires, the air flow pattern became quite different. The blocking effect to ambient air flow was quite apparent, and air flow pattern within the fire area was obviously much more complex. In these tests, the effect of the fire as a perturbation in the ambient flow became apparent soon after ignition. In general air on the windward side of the fire flowed directly into the fire at an accelerated rate. On the flanks the instrumentation usually indicated air flowing into the fire at an angle to the edge, but in some places, it appeared to be moving directly into the fire. On the downstream or lee side of the fire, the air flow direction was more erratic than in other areas, but mostly into the fire area against the prevailing ambient wind.

Although the air flow instrumentation indicated the air flow on the flanks was generally into the fire

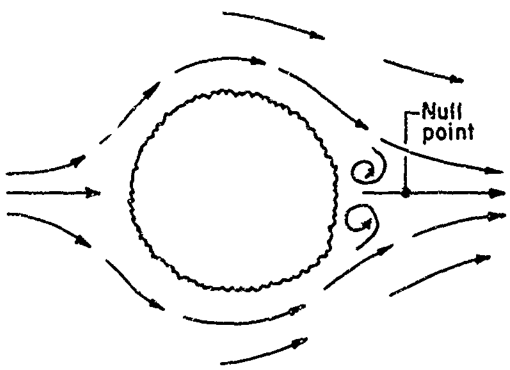


Figure 19–*Schematic of air flow around a stationary fire.*

at an angle, observations of smoke tracers around the fire indicated flow in many areas was parallel to the sides of the fire. To investigate this anomaly a small scale model of a multiple-fuel-bed fire was constructed using electrically heated "fuel beds." This model was placed in a wind tunnel and air flow traced with smoke. By carefully adjusting fuel bed temperature and air flow speed, it was possible to create a convection column and flow pattern near the surface that closely resembled what had been observed on the close-spaced fires. From this rather crude model the streamlines of air flow appeared to be as shown in figure 20. Thus whether air flow sampling at a fixed point would indicate parallel flow, flow at an angle, or direct flow into the fire would appear to be largely a matter of placement in the sensing device. Therefore, we concluded that the recorded data were consistent with what actually occurred, and that the apparent anomaly between recorded air flow and observed flow was due to the small number of sampling points.

Measurement

Air flow data were recorded by the vector anemometers described earlier for three of the Test Fires–4, 5, and 6. In the sampling procedure used, the wind speed was integrated over a 2-second period and recorded every 10 seconds. Since data were recorded at 50 to 87 stations at each fire for periods up to 5 hours, an enormous mass of data have been accumulated. Only general features of the air flow shown by these data have as yet been analyzed.

The basic air flow pattern for all of the close-spaced fuel-bed fires was similar. Since Test Fire 5 had the most extensive air flow instrumentation it has been chosen to illustrate the general pattern. In this fire, air flow data were recorded at 32 locations and at several levels at each location for a total of 72 sampling points. To provide a measure of air flow

unaffected by the fire, a control station was set up about 0.8 mile from the fire area *(fig. 21)*.

Ten-minute time intervals at various stages in the fire were arbitrarily chosen for analysis. In time after ignition these intervals were: 1 to 10 minutes, 20 to 29 minutes, 40 to 49 minutes, 50 to 69 minutes, 90 to 99 minutes, 120 to 129 minutes, 180 to 189 minutes, and 240 to 249 minutes. Average wind

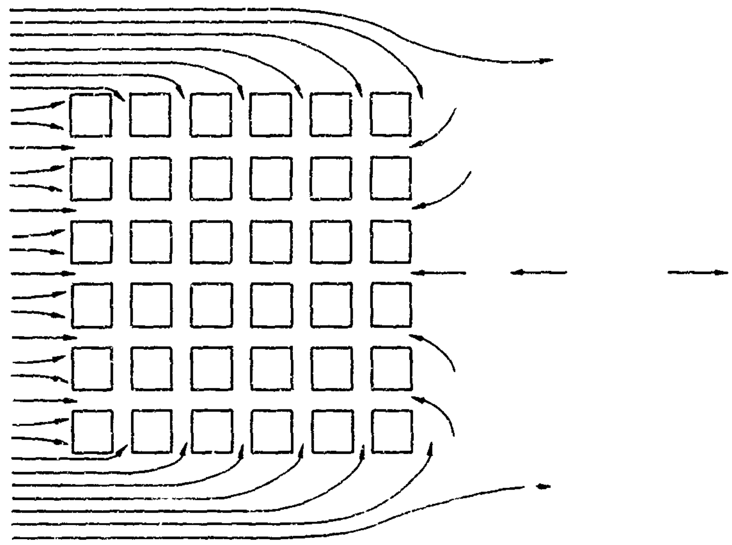


Figure 20–*Schematic of air flow around a multiple fuel bed fire, based on a model placed in a wind tunnel and air flow traced with smoke.*

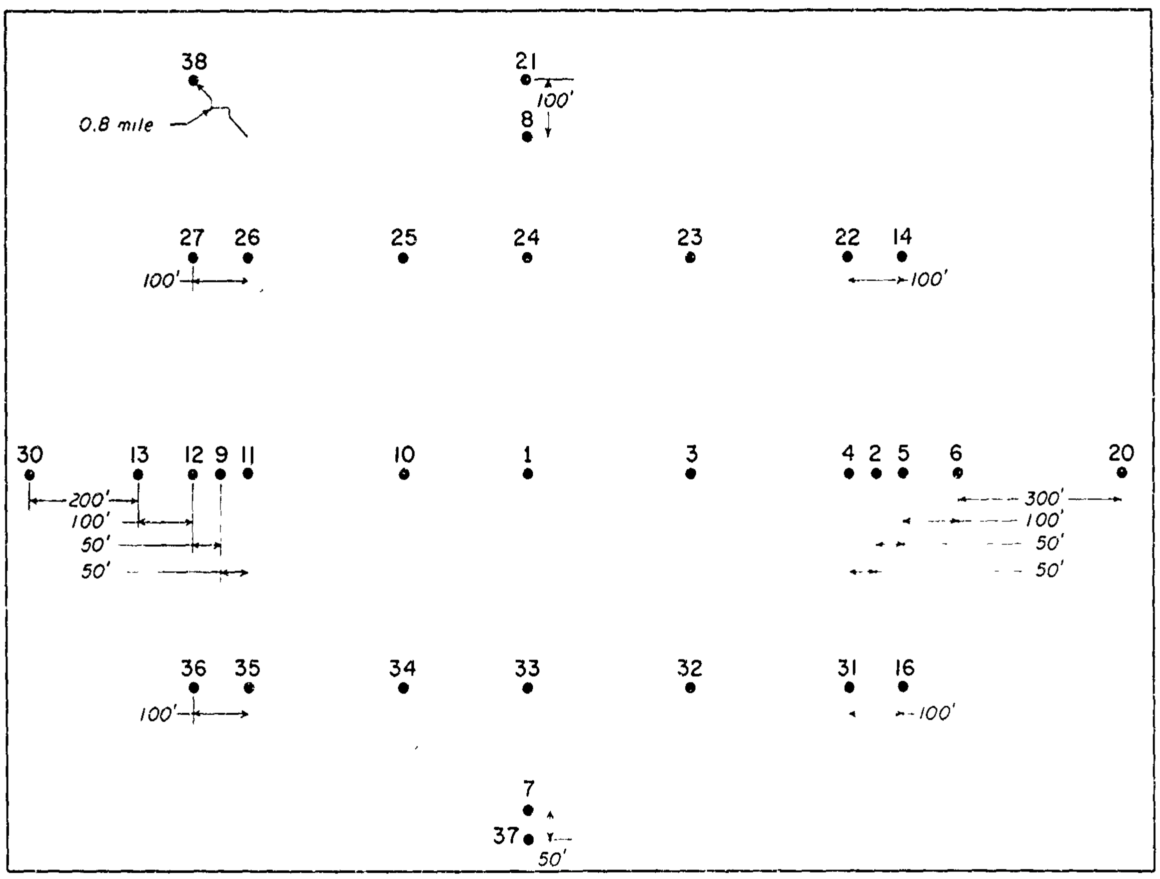


Figure 21–*Location of anemometer towers for Test Fire 5, June 14, 1966. The control tower, upper left-hand corner, was set up 0.8 mile from the fire area.*

speed for three 10-second periods around each minute were calculated, and the horizontal and vertical angles recorded for each of the three observations These data were then plotted for each station for the selected time interval. Wind direction angles were usually plotted to show the range of direction, both horizontal and vertical. If the range in direction was 15° or less, the directions were averaged.

These data showed a large fire effect in the early stages, and then a gradual decline toward ambient conditions as the fire progressed. To reduce the mass of data available, only data from the 20-foot level for portions of four of the 10-minute time periods analyzed are reported. These include data from the initial stages of the fire (1- to 10-minute time period), a time period soon after the fire peak (20- to 29-minute time period), a period in the declining stage of the fire (60- to 69-minute), and a period when only large fuel remained (120- to 129-minute). The data reported are typical for the air flow patterns during these stages of the fire.

Flow Patterns

For the first 2 minutes after ignition, the directions of the horizontal air flow and of the ambient flow were the same generally across the plot from left to right *(figs. 22, 23)*. Wind speeds were also close to ambient as indicated by the control station *(figs. 22, 23)*, although some slight fire effect can be detected in the second minute. By 3 minutes after ignition the fire had a very obvious effect on both air flow direction and speed. On the downwind side air flow was into the fire against the ambient wind, and flow into the fire on the flanks was also apparent *(fig. 24)*. Wind speeds also increased sharply, particularly on the fire edges and within the fire boundaries *(fig. 24)* The fire effect continued to strengthen as the fire built toward its peak *(figs. 25, 26)*. Air flow direction indicated that the maximum convection activity was offset somewhat downwind from the fire center, confirming visual observations of the fire. During the thermal peak the effect of fire appeared to have extended more than 500 feet on both the upwind and downwind sides. And the air flow into the fire tended to be stronger on the downwind than on the upwind side.

The flow pattern established in the early stages of the fire had not changed materially by the second time-period analyzed. The fire effect appeared to have diminished somewhat, but air speeds near the fire and within the fire boundaries were still substantially above ambient, and the effect on flow direction was still strong *(figs 27, 28)*. By then, however, the fire effect did not extend out more than 400 to 500 feet from the fire edge.

The air speed recorded on Tower 1 suggested that a fire whirl formed at or near this location *(fig. 27)*. The speed of this whirl 20 minutes after ignition averaged 63 ft./sec. Its peak speed was 122 ft./sec. and may actually have been greater since the capacity of the anemometer apparently was exceeded.

Air flow continued to be stronger on the downwind side, but at Tower 20, it was relatively weak and variable *(fig. 28)* indicating the null point in the air flow pattern around the fire was near there.

In the third time period, wind speeds were slightly lower than the second period and flow direction more erratic *(figs. 29, 30)*. Numerous vortices formed in the downwind portion of the fire during this stage of the fire. This activity was reflected in the generally higher wind speeds in this area. Another fire whirl apparently passed near Tower 22 at the 60-minute mark as indicated by the speed and direction there *(fig. 29)*.

By 120 minutes after ignition about 85 percent of the fuel had burned, and fire activity had dwindled to a low level. Only the larger fuel elements remained, and flame heights generally were only 2 or 3 feet. Much glowing material remained in the fuel beds, however, and considerable heat was still being produced. Vortices in the form of dust devils also appeared frequently in all parts of the fire area, although vortex action was still predominate on the downwind side. Ambient air flow was beginning to predominate, but it was obvious that the fire still affected the air flow *(figs. 31, 32)*.

As might well be expected, the fire had a major effect on the vertical air flow pattern. The peak vertical component during three observations at any 1 minute was plotted. And where both negative (downflow) and positive (upflow) occurred both are shown *(figs. 33-39)*. Horizontal flow is indicated only when no vertical flow occurred in any of the three observations.

Before ignition and during the first minute, horizontal flow predominated at all stations *(fig. 33)*. Vertical flow began to appear in the second minute *(fig. 37)* and continued to increase as the fire built in intensity *(figs. 35-37)*. During the first . minutes nearly all vertical flow was within the fire boundary or at the fire edge, and was both positive and negative.

By 5 minutes after ignition a negative vertical component was obvious at the center of the downwind side *(fig. 37)*. The tendency toward negative vertical flow persisted into the second time period

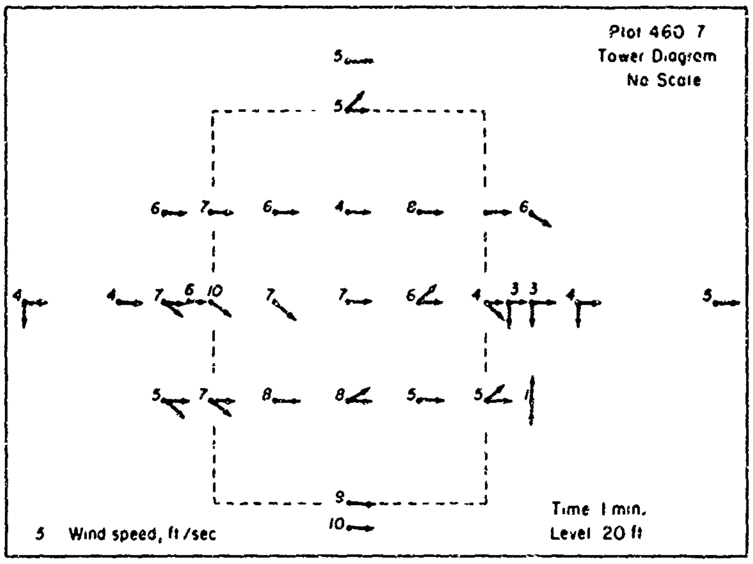


Figure 22–*Pattern of air flow and speed at 1 minute after ignition in Test Fire 5, June 14, 1966.*

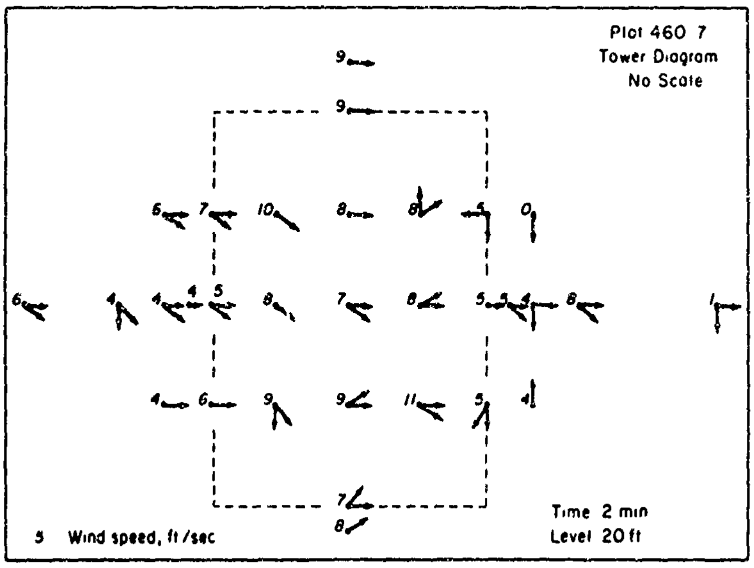


Figure 23–*Pattern of air flow and speed at 2 minutes after ignition in Test Fire 5, June 14, 1966.*

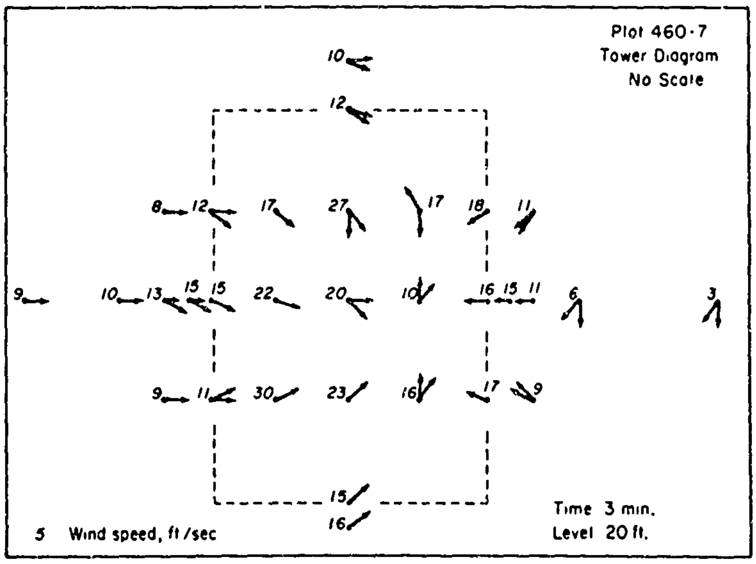


Figure 24–*Pattern of air flow and speed at 3 minutes after ignition in Test Fire 5, June 14, 1966.*

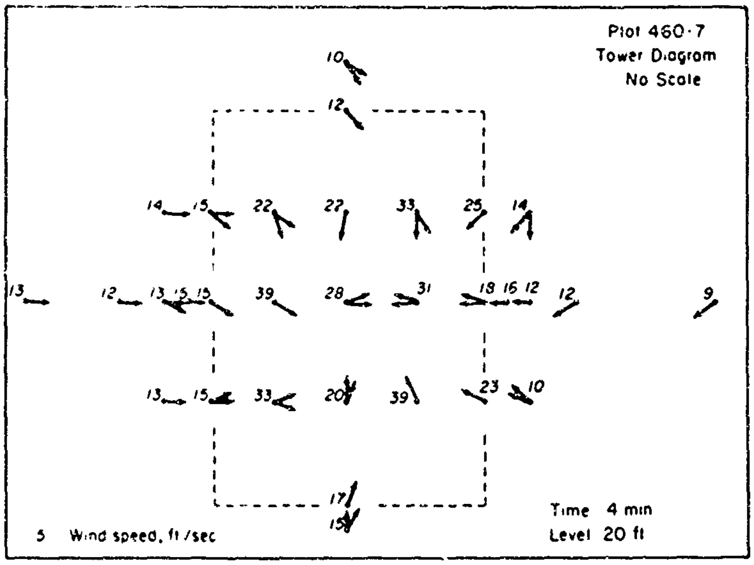


Figure 25–*Pattern of air flow and speed at 4 minutes after ignition in Test Fire 5, June 14, 1966.*

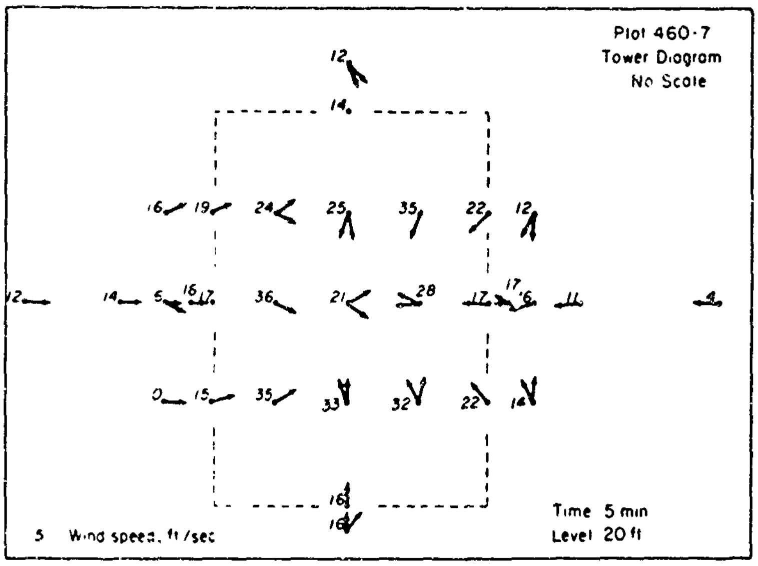


Figure 26–*Pattern of air flow and speed at 5 minutes after ignition in Test Fire 5, June 14, 1966.*

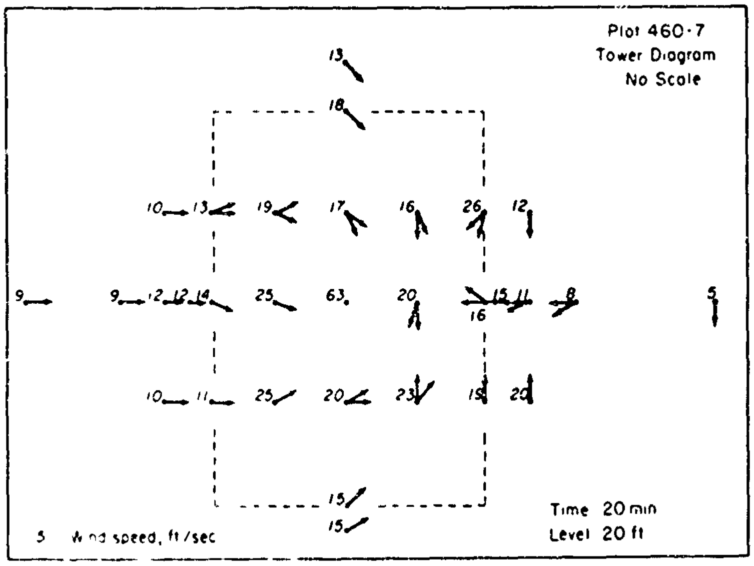


Figure 27–*Pattern of air flow and speed at 20 minutes after ignition in Test Fire 5, June 14, 1966.*

Figure 28–*Pattern of air flow and speed at 21 minutes after ignition in Test Fire 5, June 14, 1966.*

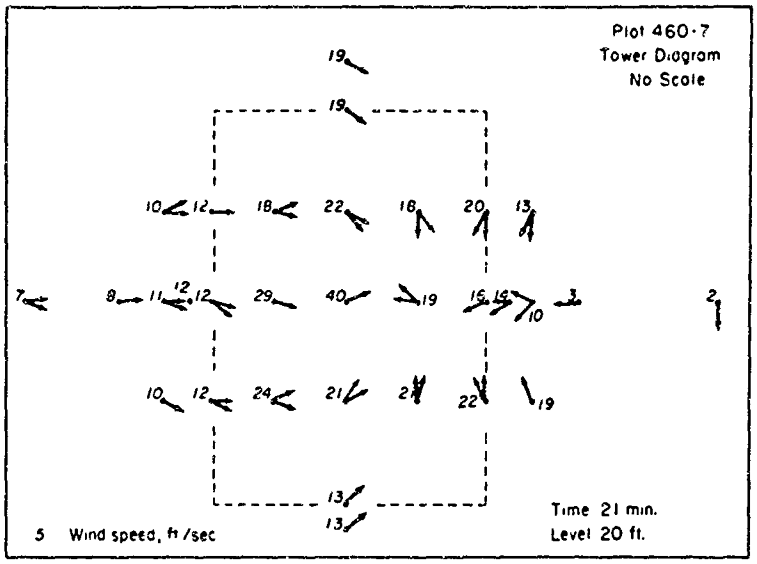


Figure 29–*Pattern of air flow and speed at 60 minutes after ignition in Test Fire 5, June 14, 1966.*

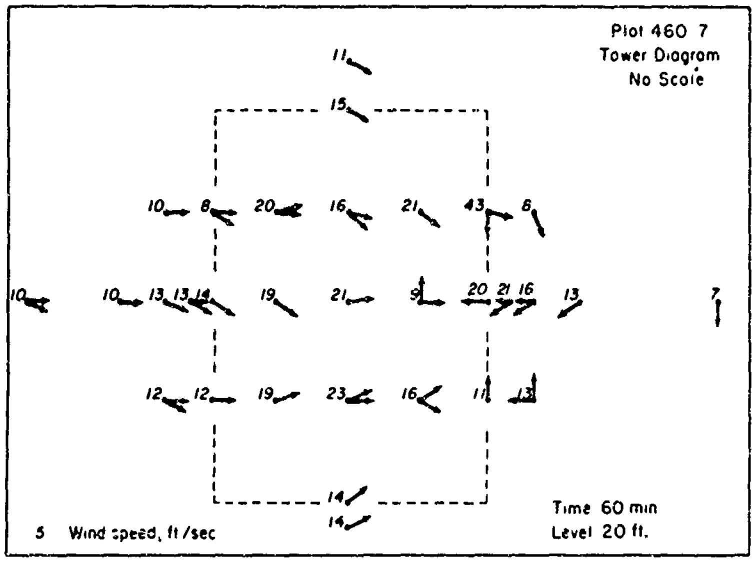
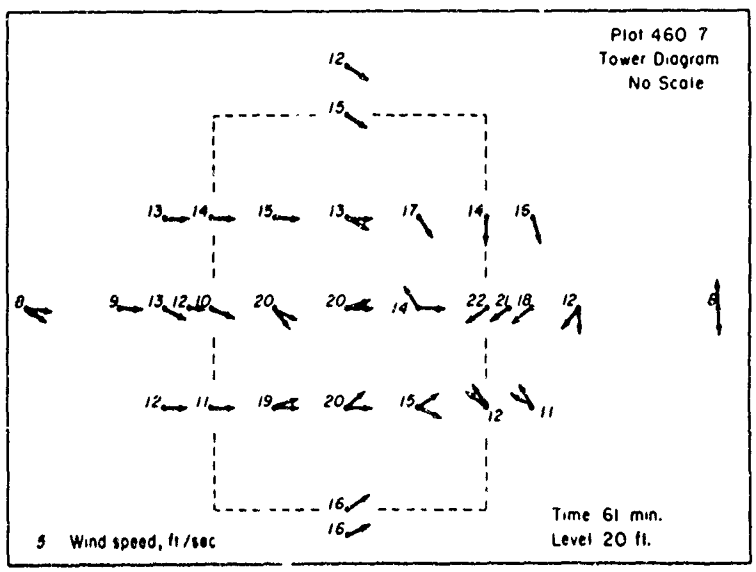


Figure 30–*Pattern of air flow and speed at 61 minutes after ignition in Test Fire 5, June 14, 1966.*



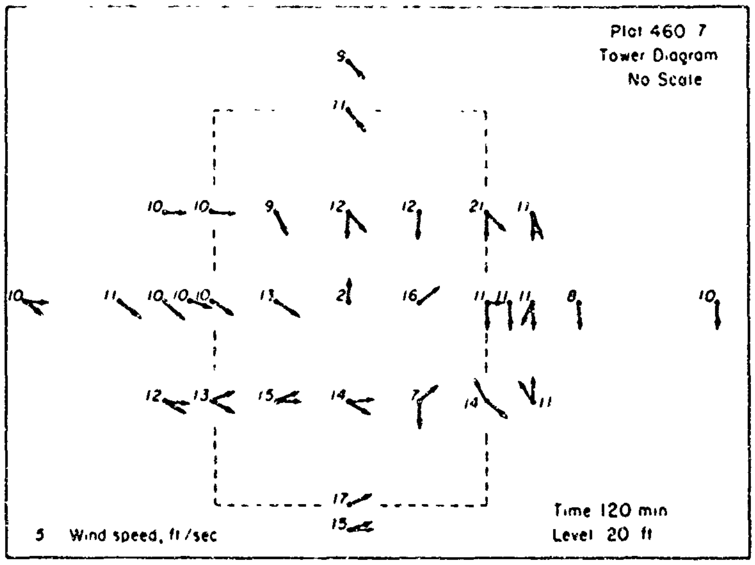


Figure 31–*Pattern of air flow and speed at 120 minutes after ignition in Test Fire 5, June 14, 1966.*

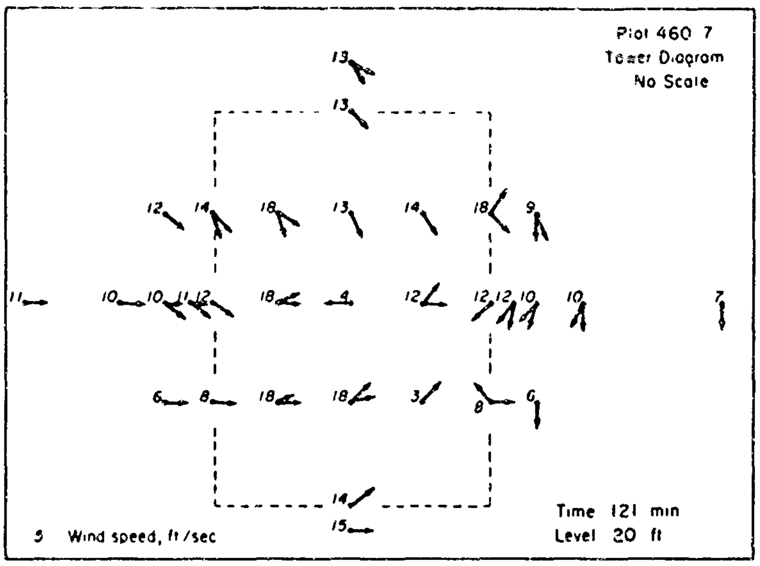


Figure 32–*Direction of air flow and speed at 121 minutes after ignition in Test Fire 5, June 14, 1966.*

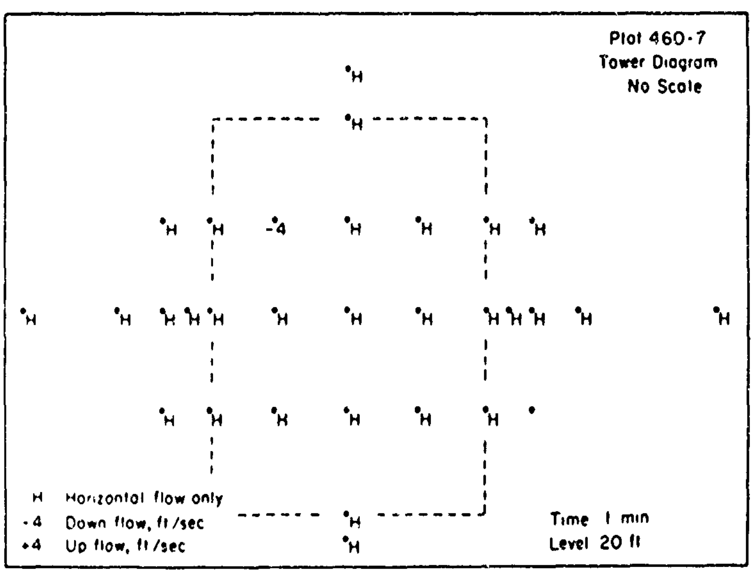


Figure 33–*Pattern of horizontal flow at 1 minute after ignition in Test Fire 5, June 14, 1966.*

Figure 34–*Pattern of horizontal flow at 2 minutes after ignition in Test Fire 5, June 14, 1966.*

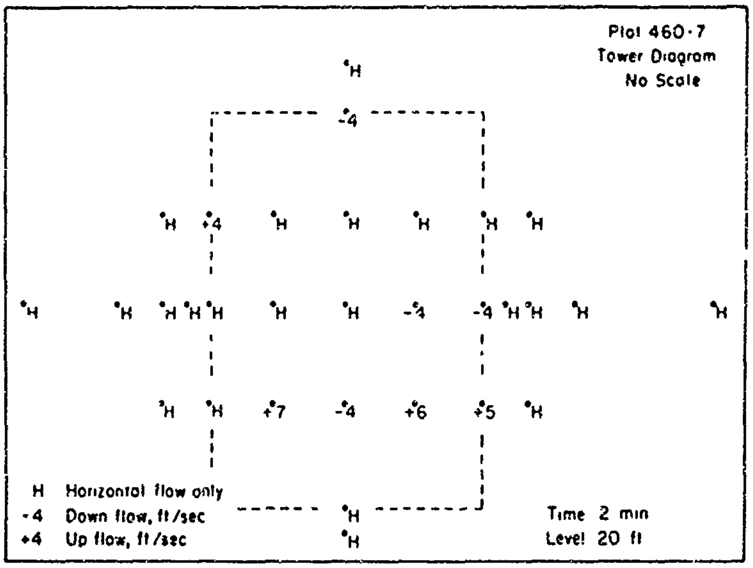


Figure 35–*Pattern of horizontal flow at 3 minutes after ignition in Test Fire 5, June 14, 1966.*

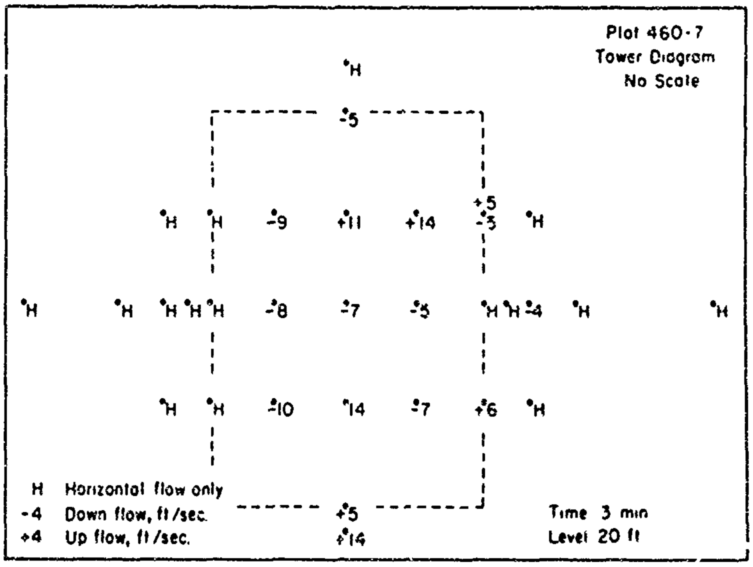
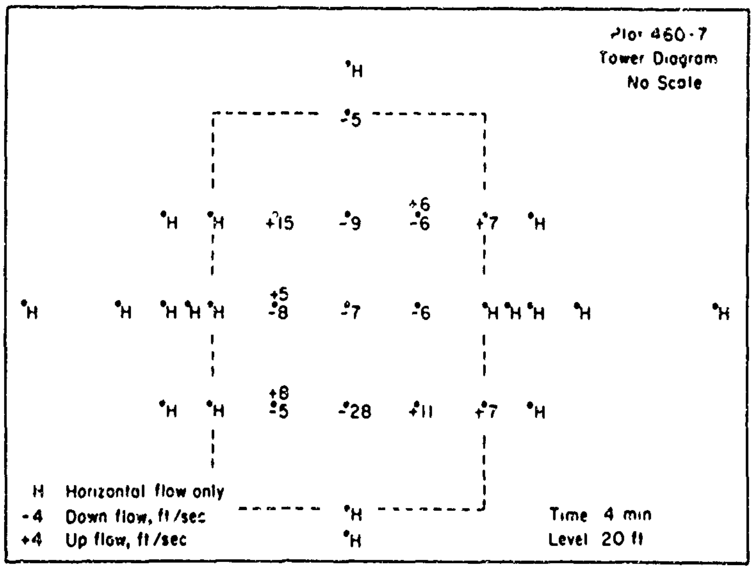


Figure 36–*Pattern of horizontal flow at 4 minutes after ignition in Test Fire 5, June 14, 1966.*



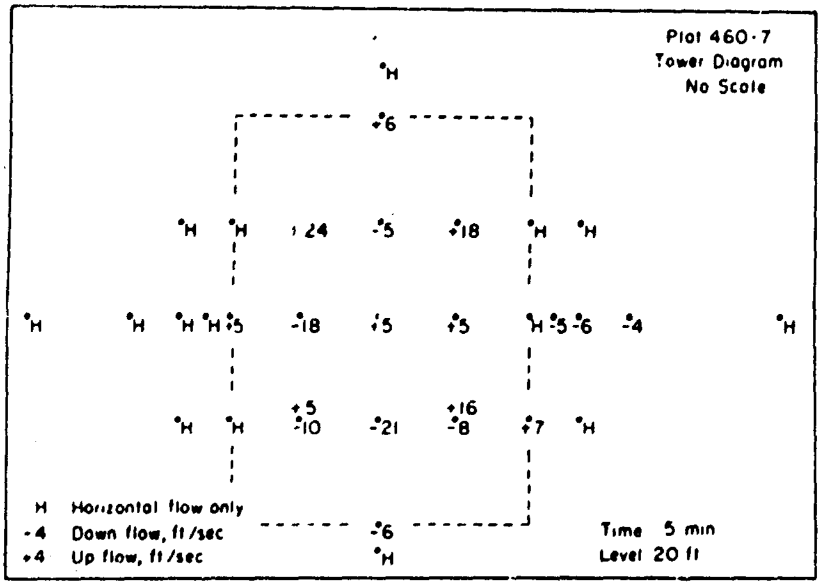


Figure 37–*Pattern of horizontal flow at 5 minutes after ignition in Test Fire 5, June 14, 1966.*

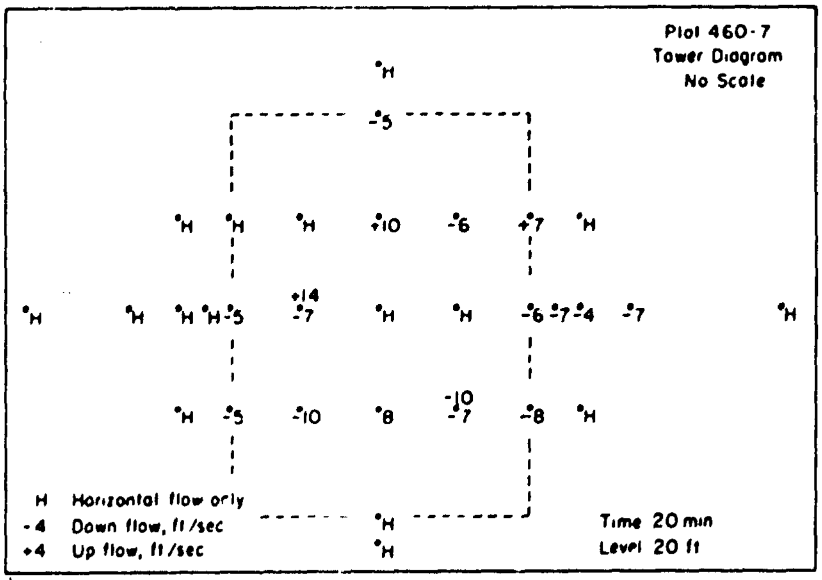


Figure 38–*Pattern of horizontal flow at 20 minutes after ignition in Test Fire 5, June 14, 1966.*

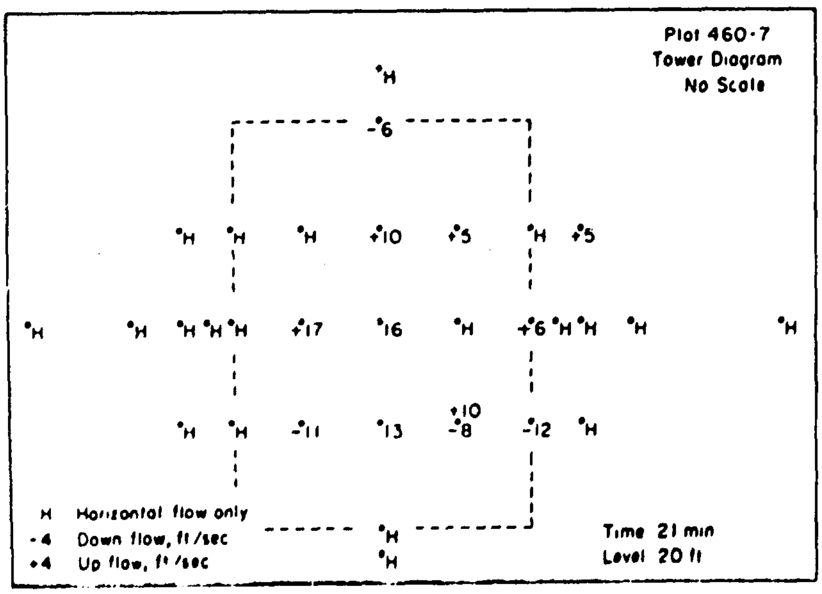


Figure 39–*Pattern of horizontal flow at 21 minutes after ignition in Test Fire 5, June 14, 1966.*

Figure 40- *Pattern of horizontal flow at 60 minutes after ignition in Test Fire 5, June 14, 1966.*

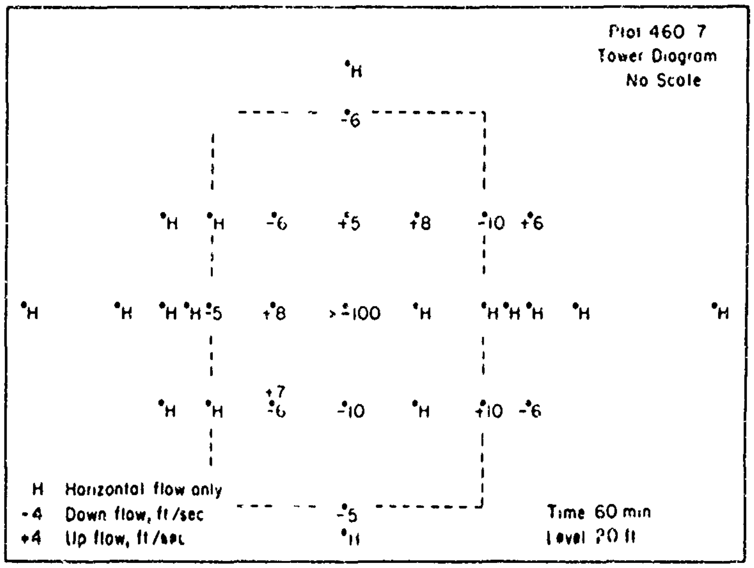


Figure 41–*Pattern of horizontal flow at 61 minutes after ignition in Test Fire 5, June 14, 1966.*

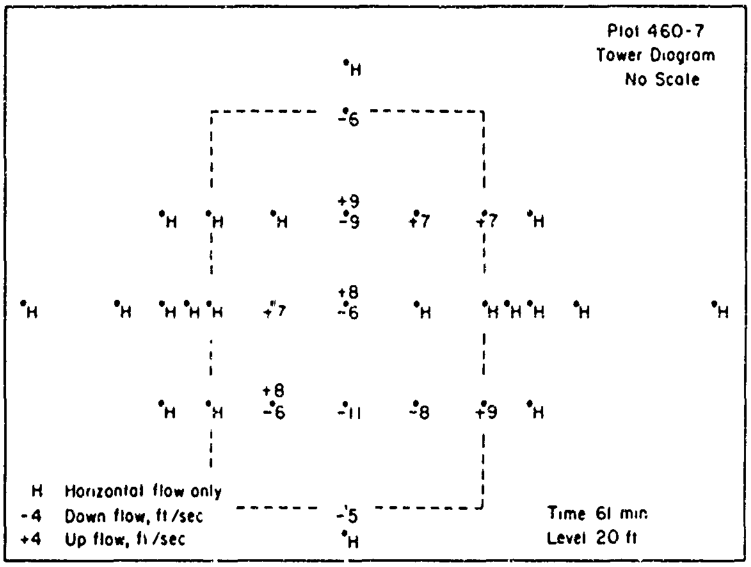
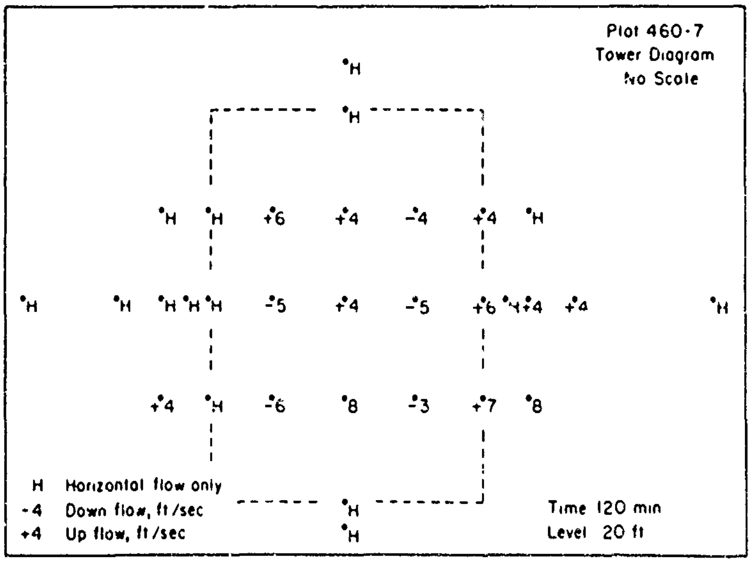


Figure 42–*Pattern of horizontal flow at 120 minutes after ignition in Test Fire 5, June 14, 1966.*



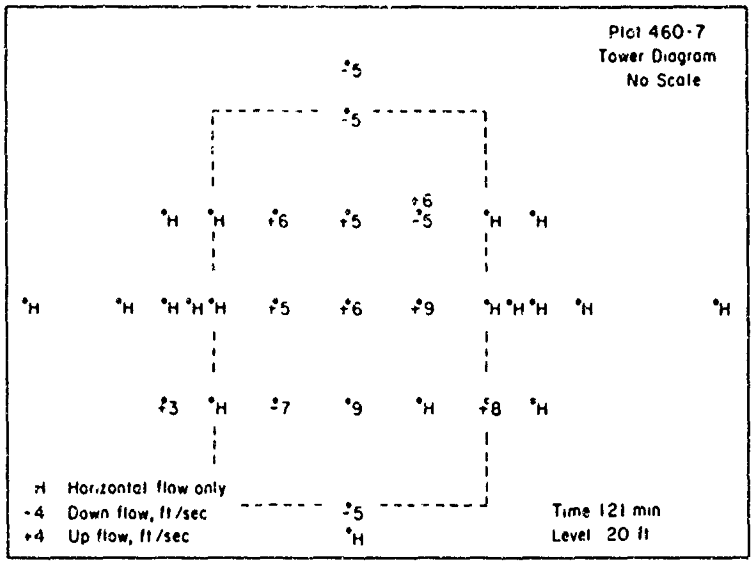


Figure 43—*Pattern of horizontal flow at 121 minutes after ignition in Test Fire 5, June 14, 1966.*

(fig. 38) along with both positive and negative components in the rest of the fire area. The negative component on the downwind side at the 20-foot level was not continuous, but sometimes switched to horizontal or positive flow *(fig. 39)*.

At 60 minutes after ignition the vertical air flow at the fire edge and within the fire boundaries still remained, and sometimes extended to the downwind side of the fire *(figs. 40-41)*. As in the second time period the vertical flow was both positive and negative. The effect of the fire whirl at Tower 1 at the 60-minute mark was also evident *(fig. 40)*.

Vertical air flow components were evident in the flow pattern as late as 120 minutes *(figs. 42, 43)*, although generally much weaker and more variable than in the early stages of the fire.

Throughout the active fire period both air flow instrumentation and visual observations indicated strong air flow and turbulence within the fire boundaries, with a much less pronounced effect at the fire exterior. This characteristic was noted in all multiple and single fuel-bed tests.

Observations at ground level of all of the close-spaced, fuel-bed fires showed areas around the perimeter of the fire which permitted a view deep into the fire area. These areas were from the windward side of the fire, near the center of the lee side, and to a lesser extent on the flanks near the downstream edge of the fire. Aerial photos taken of Test Fire 5 showed an air flow pattern that confirmed these observations. On the lee side and on the flanks there were large hemispherical areas almost clear of smoke. On the windward side the smoke was held near the ground over nearly 40 percent of the plot by the ambient wind *(fig. 44)*. Study of time lapse photos and reports from observers on the ground indicated a strong tendency for downward flowing air in these areas. This was confirmed to some extent by the air flow instrumentation; however, much of this downflow seemed to be occurring above the level of instrumentation. The air flow patterns indicated by photography, instrumentation, and ground observations seemed to indicate a center of low pressure near ground level and under the main convection column. Flow toward this area was both horizontal and vertical.

The chaotic air flow pattern within the multiple-fuel-bed fires seems to be associated with the burning pattern of the fuel beds. During the most active flaming period of the fire each fuel bed maintains a separate convection column of varying heights. Each fuel bed column may often break up into two or more separate columns. The heated air and gases in the columns seldom rise smoothly, but almost immediately develop vortex rings, with the flow at the top being outward and relatively downward along the sides as the vortex rises. Sometimes the vortex ring appears to have a central core of rising gas; in other cases, the rings may appear as a series of rising bubbles with clear air between. The individual columns expand as they rise and the vortex rings and convection bubbles begin to intermingle. As the columns continue to rise they finally merge into a single column, with the vortex rings and convective bubbles appearing on a larger scale. The turbulent area between the flames and the merged columns is the transition zone of the Countryman descriptive model *(fig. 1)*.

The air flow in the transition zone is complicated by the tendency of the convection columns to lean in

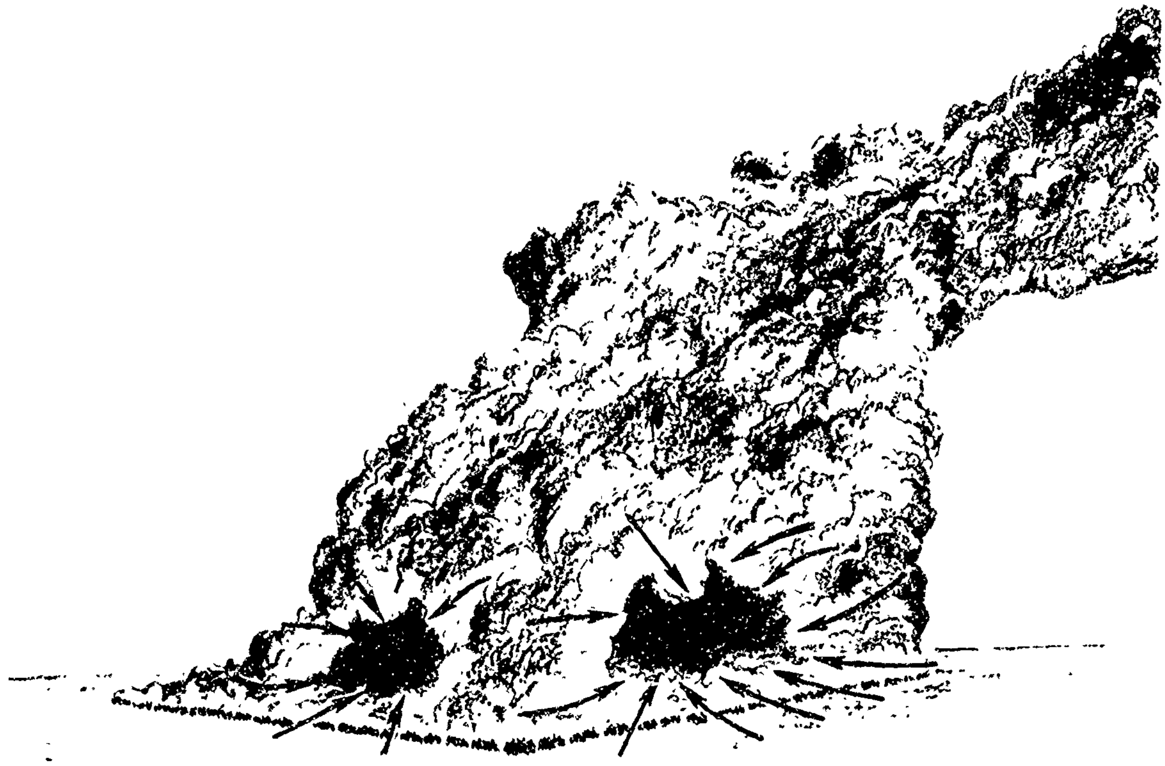


Figure 44–*Sketch based on several photos shows strong inflow areas in all of the close-spaced, fuel-bed fires. Arrows point to the direction of air flow.*

various directions–in some cases, almost horizontally. Thus the flow is not strictly up or down but may assume almost any angle. Measured air flow in the fire interior generally showed a strong horizontal component and rarely a vertical component alone. Often two levels on the same instrument tower showed the vertical flow to be in opposite directions.

The highly complicated flow within a fire area can be illustrated by the air flow data taken around milled fuel bed 2 in Test Fire 6 *(fig. 15)*. In this fire anemometer towers were located in the "streets" on all four sides of the milled beds. The vector air speeds in feet per second and showing the vertical flow directions at various heights were plotted for a period near the fire peak for each tower at fuel bed 2; an azimuth arrow shows horizontal direction.

The "streets" in Test Fire 6 did not run in true north-south and east-west directions. To simplify data analysis, however, we oriented the anemometers with the "streets" instead of cardinal directions. With this orientation the ambient air flow direction would appear as approximately southwest and the convection column as leaning toward the northeast.

Turbulent air flow was evident at all towers and at all levels, with air speeds and directions fluctuating widely. Despite the highly variable air flow, individual towers tended to show different patterns. At tower 6 on the upwind side of the fuel bed the flow at low levels was generally toward the fuel bed and at high speed *(fig. 45)*. Vertical components at these levels were usually slight. At the 20-foot level the horizontal air flow direction was consistently toward fuel bed 2 and at moderate speeds. The vertical component was small and usually directed upward, although some intermittent downflow was also evident. Air flow at the 50-foot level was also toward the fuel bed and at speeds nearly double that at the 20-foot level The vertical component, although small, was consistently directed upward.

The air flow at tower 8 on the downwind side of

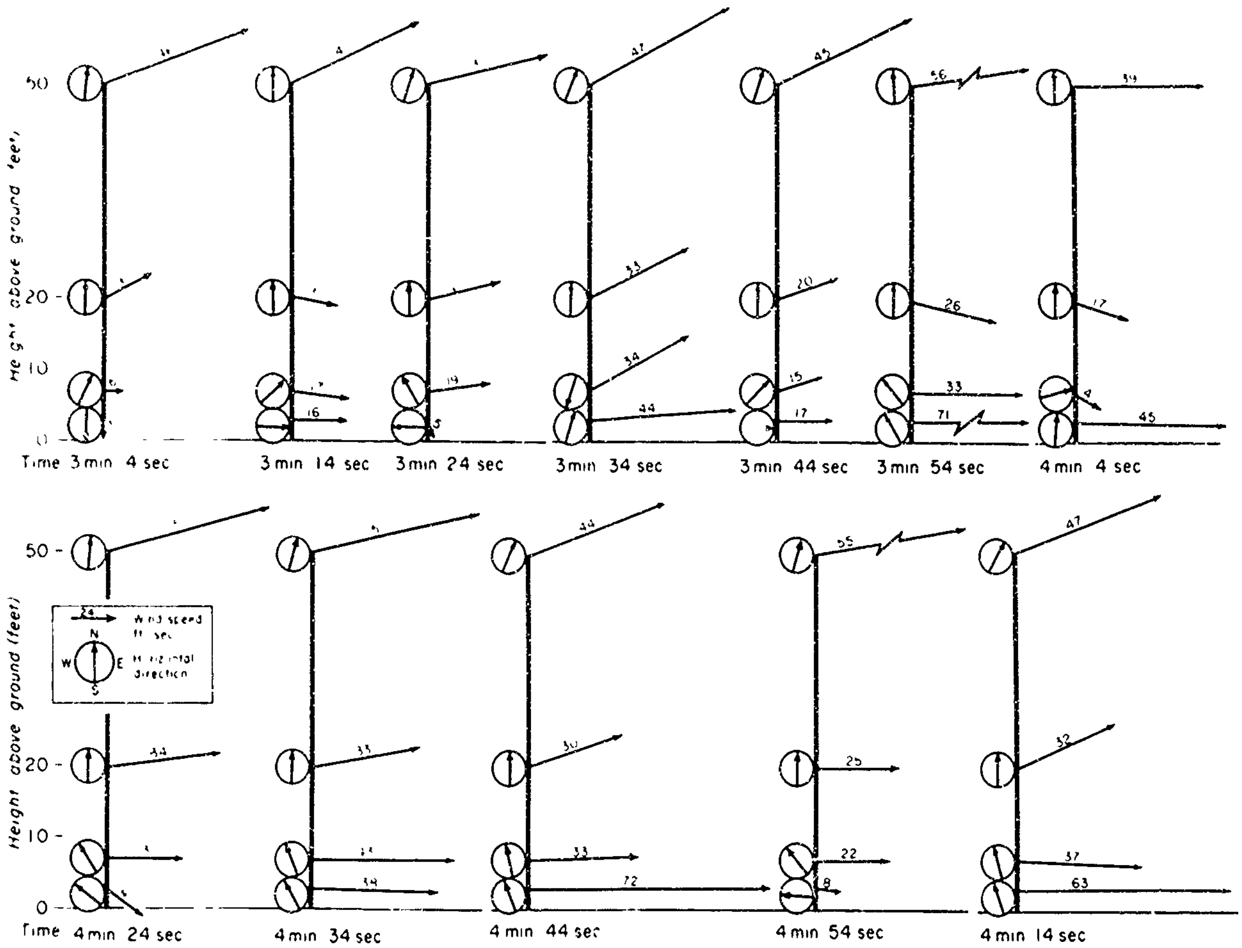


Figure 45–*Air flow pattern at tower 6, Test Fire 6.*

the fuel bed was much more erratic in both speed and direction than that at tower 5 *(fig 46)*. At the 3.5- and 7-foot levels the horizontal flow was sometimes directed toward the fuel bed and sometimes away from it. Wind speed at the 20-foot level tended to be greater than at the 50-foot level. And strong downward components appeared at both the 20- and 50-foot levels.

At tower 7 on the west side, the flow was generally along the north-south "street" at all levels *(fig 47)*. Air speed at the 20-, 50-, and 70-foot levels was much the same. At the 20-foot level the flow was nearly horizontal. The 50-foot level showed a predominately downward flow. And at the 70-foot level, an upward component persisted.

Air flow at the 3.5- and 7-foot levels on tower 7 was more erratic in both speed and direction than at the higher levels The speed at 7 feet was often greater than any of the other levels For both the 3.5- and 7-foot levels the vertical component was consistently directed upward.

Tower 5 on the east side of fuel bed 2 was probably closer to the convection column from this fuel bed than any of the other towers. The vertical wind component at this tower was always directed upward at all levels and sometimes was very strong *(fig. 48)*. At 3 minutes and 44 seconds, for example, the vector air speed at the 70-foot level was 80 ft./sec. and very nearly vertical. Similar strong vertical components appeared at 3 minutes, 24 seconds; 4 minutes, 14 seconds; and 4 minutes, 24 seconds. Horizontal flow direction was also relatively consistent at all levels at this tower.

Effects of Fire

The air flow patterns in and around the Flambeau test fires showed consistent patterns for a given fuel bed arrangement. In the single-fuel-bed test, the fire blocked the ambient wind, with turbulence and eddies forming in the wake of the fire. Little direct inflow into the sides of the fire could be detected. The same flow pattern appeared around individual

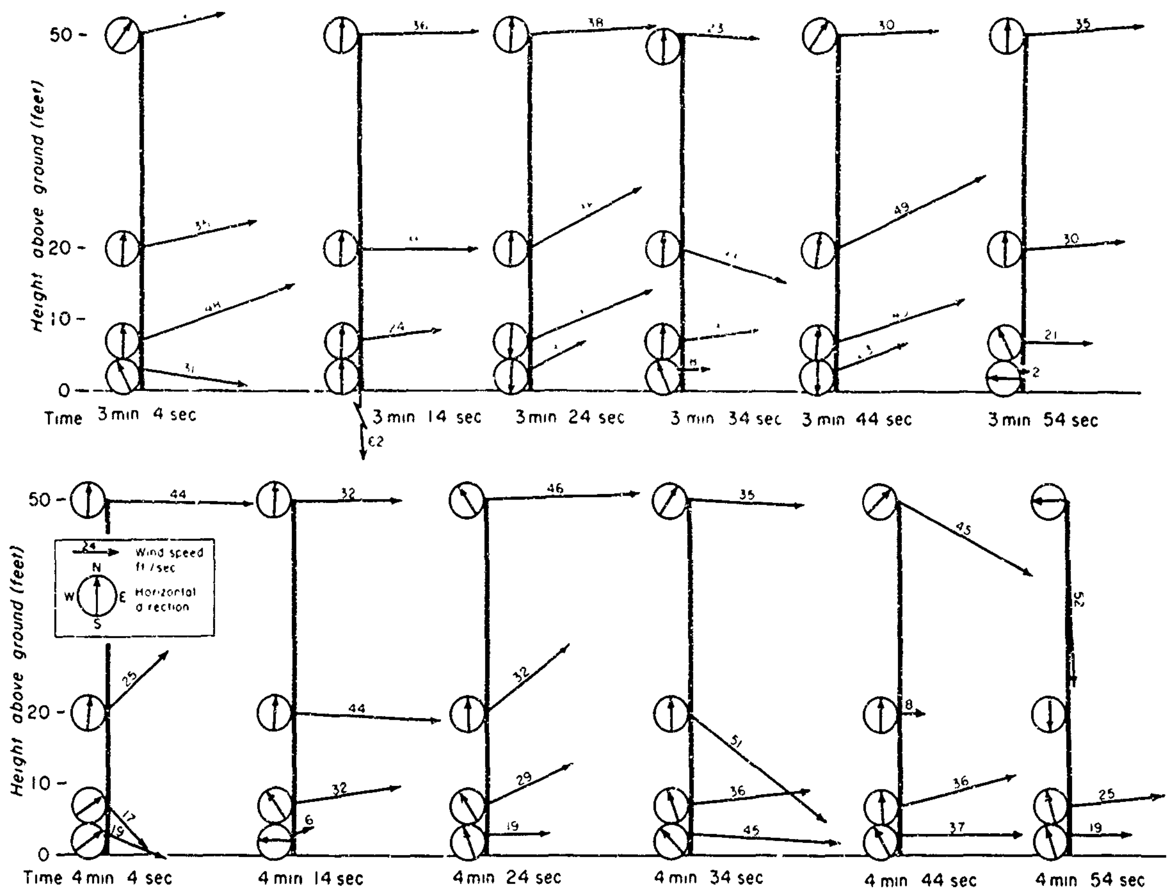


Figure 46—*Air flow pattern at tower 8 in Test Fire 6, September 29, 1967.*

fuel beds in the multiple-fuel-bed fires, where the fuel beds were wide-spaced. In addition, air flow in the "streets" within the fire boundaries was accelerated in the direction of the ambient flow. This acceleration is probably due to convergence of the ambient flow between the fires and to an added vertical component. The wide-spaced fuel-bed fires as a whole appeared to block weakly the ambient flow, and some flow into the sides of the fire was noted.

The effect of the fire on the air flow was much more pronounced in the close-spaced fuel bed fires. Here the blocking effect was similar to that in the single-fuel-bed fires, with turbulence and inflow developing on the lee side. Air inflow into the sides of the fire was also pronounced. Whether the air flow sensor indicated flow directly into the fire or at an angle depended upon the location of the instrument. Although the air flow outside the fire boundaries was appreciably stronger than the ambient flow, it did not reach the hurricane speed often believed associated with mass fires.

Within the fire boundaries of the close-spaced fuel-bed fires the air flow was extremely turbulent, with strong horizontal and vertical components. Speeds in excess of 100 ft./sec. were recorded and may have gone much higher. Air entrainment into the fire area appeared to originate from both the ring vortices created in the numerous small convection columns in the combustion and transition zones and the direct flow into the fire between the convection columns.

The tendency of the individual columns to lean with the ambient wind and for the columns and their ring vortices to intermingle has a major influence on the air flow at any one location. For example, the air flow between two fuel beds may be influenced by the fire in one fuel bed at the lower levels and by the convection column of the other fuel bed at higher levels. Since any array of natural fuel beds, urban or wildland, are not likely to burn uniformly, air flow characteristics will depend strongly on the burning pattern of the fire.

Although the development of separate small convection columns is perhaps more "orderly" in the multiple-fuel-bed fires, this same characteristic appears in large continuous fuel bed fires. Here the

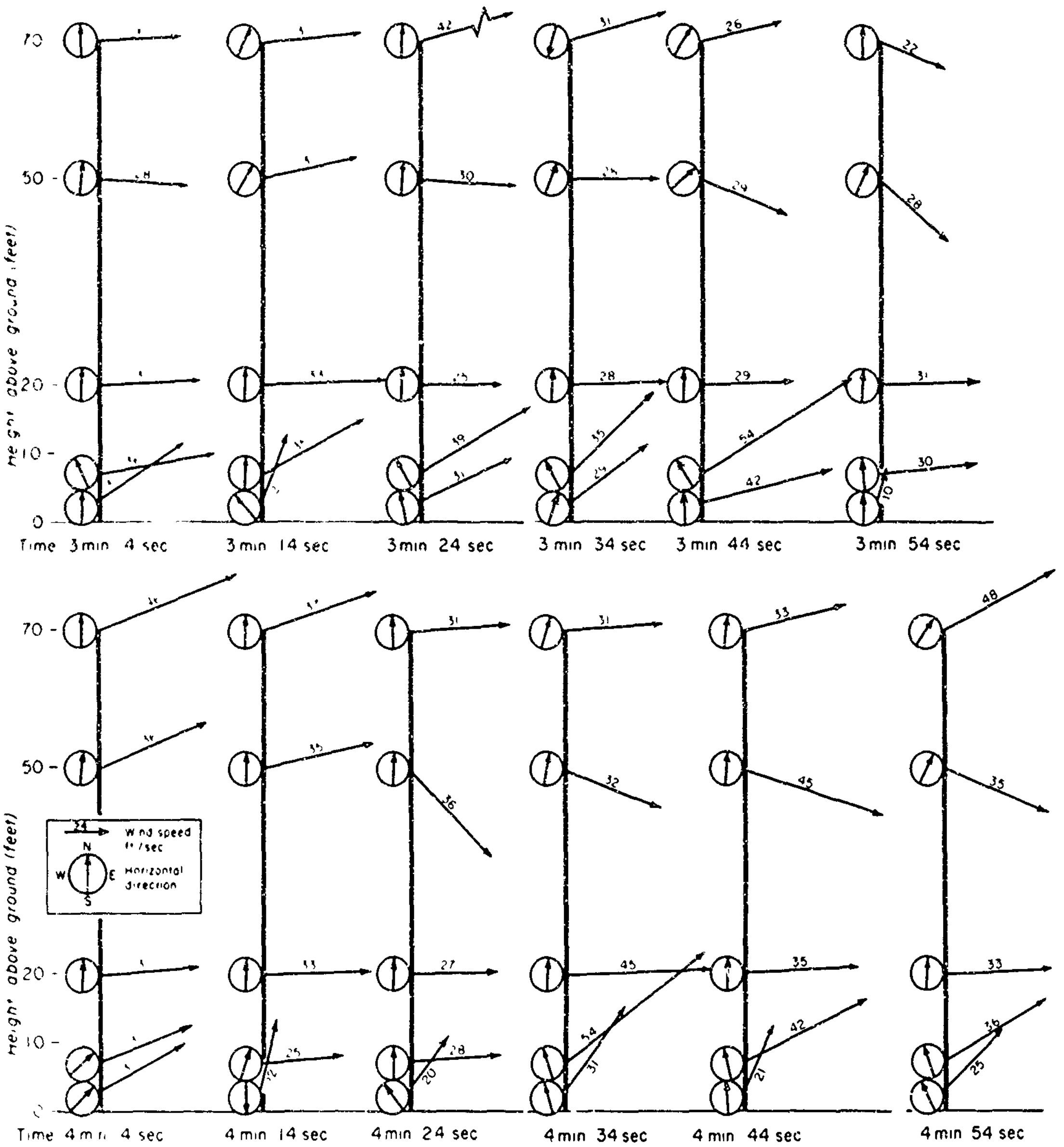


Figure 47—*Air flow pattern at tower 7 in Test Fire 6, September 29, 1967.*

columns occur randomly and move about during the fire. However, the downward flow components appear to be present along with "lanes" for air access to the interior of the fire between the individual small columns. In the Project Flambeau tests, there was little tendency for a large fire area to merge into one gigantic flame, but rather a strong tendency toward breakdown of the fire area into many smaller fires.

An interesting and perhaps important phenomenon in the close-spaced fuel plots was the development of areas of strong inflow in the lee and flanks of the fire. In Test Fire 5, this flow tended to divide the fire into four separate convection columns within the transition zone. In Test Fires 2 and 6, we noted a tendency for two columns to develop. In Test Fire 4, which burned slowly, this tendency was less pronounced, however, a deep indentation on the lee side was apparent.

The tendency for a fire to break up into more than one column appears after the fire is well developed. It it not clear, however, whether the tendency for more than one convection column to form marks the beginning of a new convection pattern or simply a weakening of the fire convective system as the thermal energy output drops. With the fuels and fuel bed loading used in Flambeau a high level of thermal energy output was maintained for a relatively short time—possibly too short to permit the development

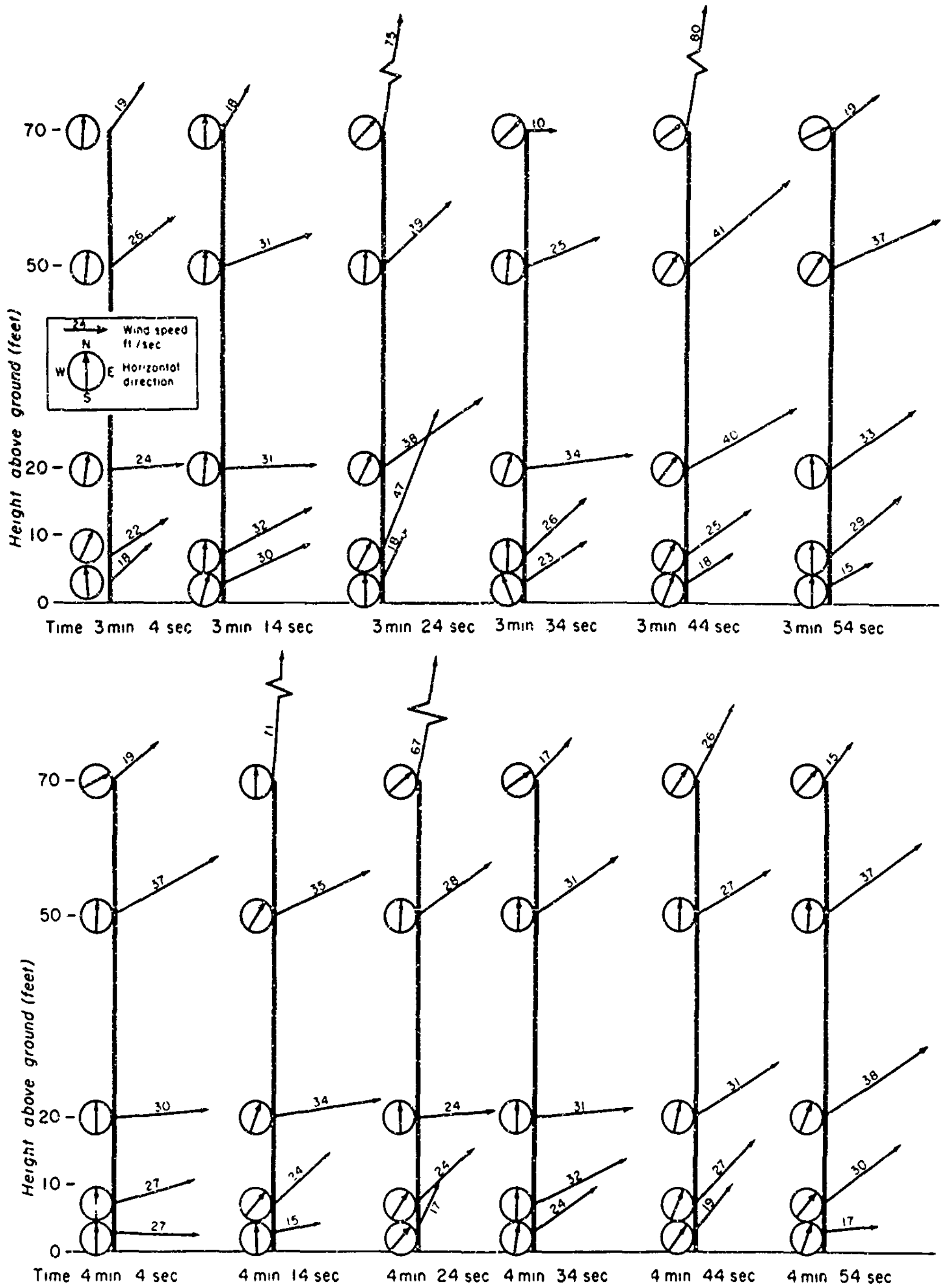


Figure 48—*Air flow pattern at tower 5 in Test Fire 6, September 29, 1967.*

of multiple large columns. In large wildland fires, multiple columns are not unusual, but their mode of development has not been described.

If the appearance of multiple large columns is actually a phase in the development of the fire system, it is of interest to speculate on the importance of the phenomenon. It is likely that as the size of the fire increases, there will be more opportunity for inflow patterns to develop that can create more such columns. One important result would be the opening of the fire interior to a fresh air supply and a decreased chance of oxygen starvation of interior fire areas. Thus sheer size of the fire would not limit burning.

The spatial thermal pattern for a large fire, natural or nuclear-induced, is very unlikely to be symmetri-

cal Hence, air flow patterns around and into the columns also would not be symmetrical. With a number of fire areas of different thermal output rates and various sized columns, it is possible that flow patterns conducive to the growth of large vortices will develop

Thermal Radiation

The role of thermal radiation in fire spread and other fire phenomena has received considerable attention, particularly in theoretical and mathematical work Radiation is also a major consideration in civil defense activities where protection against thermal radiation in a fire is a necessity.

The relative importance of radiation in the heat balance of a fire is uncertain. Vehrencamp (1955) in studying a crib fire 50 feet in diameter calculated that about 30 percent of the heat energy of the fire was produced by radiation. After testing small wood cribs, McCarter and Broido (1965) put the radiation value at 43 percent. Fons, et al. (1960b), also using small wood cribs, calculated radiant energy at 18 percent. Despite the uncertainty of the amount of radiant energy produced by a fire, radiation is one of the basic thermal characteristics of a fire.

Measurements

Flat plate radiometers were used to measure thermal radiation for most of the Flambeau fires. These measurements were made to determine the radiant energy to which a target outside the fire area would be subjected, and to aid in the interpretation of other quantitative fire data, visual observations, and pictorial data. Of the multiple fuel bed fires burned the most complete and reliable radiation data

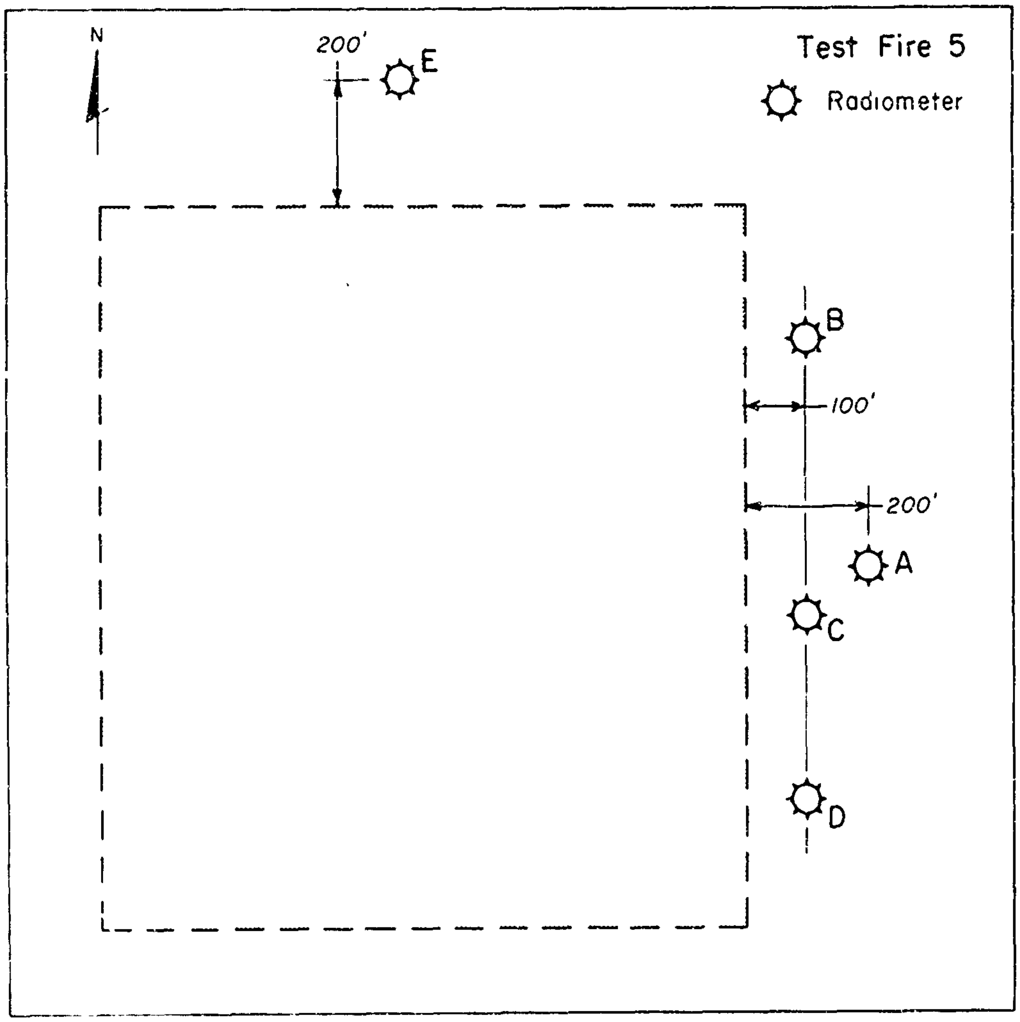


Figure 49 *Radiometers were placed at five different sites in Test Fire 5, June 14, 1966, to measure thermal radiation.*

were obtained for Test Fires 5 and 6. Portions of the data from these fires have been selected for analysis here as an illustration of the kind of information that can be derived from this type of instrument.

In Test Fire 5, radiometer locations A, B, C, and D were on the downwind side of the fire, while location E was on one flank *(fig. 49)*. All radiometers were 10 feet above ground level and 100 feet from the fire edge, except at location A, which was 200 feet from the fire. Output of each radiometer was scanned nine times per minute.

The thermal pulse from Test Fire 5, as indicated by the radiometers, had the same general form at all locations. However, there were minor variations at the different locations that were indicative of the fire and smoke patterns for the part of the fire viewed by the radiometer.

Each radiometer had a 180° field of view. Therefore radiation levels at the center location (C) should be highest since the radiometer closer to the fire corners would view more nonfire area. This was not the case, however, in the early part of the fire. At location B *(fig. 50)*, the thermal radiation rose quickly to a peak exceeding 2,900 Btu/ft.^{2}/hr., the highest level reached at any of the radiometer sites. Peak radiation at locations C *(fig. 51)* and D *(fig. 52)* were nearly equal, with rates of 2,457 Btu/ft.^{2}/hr. and 2,369 Btu/ft.^{2}/hr. respectively. At location D the peak radiation occurred slightly ahead of the one at the center location (C), and a preliminary peak at location B also appeared before the peak at C.

The relatively low rate and the lag in peak radiation at the center station may have been due partly to the ignition method, but to a greater extent to the air circulation pattern that developed as the fire built up. In this test fire, the ignition was by rows, beginning on the outside edge on each flank and moving toward the center row. About 32 seconds were required to complete the ignition sequence. As a result of the ignition pattern the fire built up more quickly on the flank edges. This condition was reflected in the slightly later time of peak radiation at the center location as compared with locations B and D.

The radiometer at location C was looking into one of the major inflow areas described earlier for this fire. In the early stages, the flames there were held close to the ground by inflowing air, and fuel beds beyond the outside row were partially obscured by low level smoke. And probably the air above the fire in this area was also relatively cool. This fire behavior would also contribute to a lower radiation rate at the

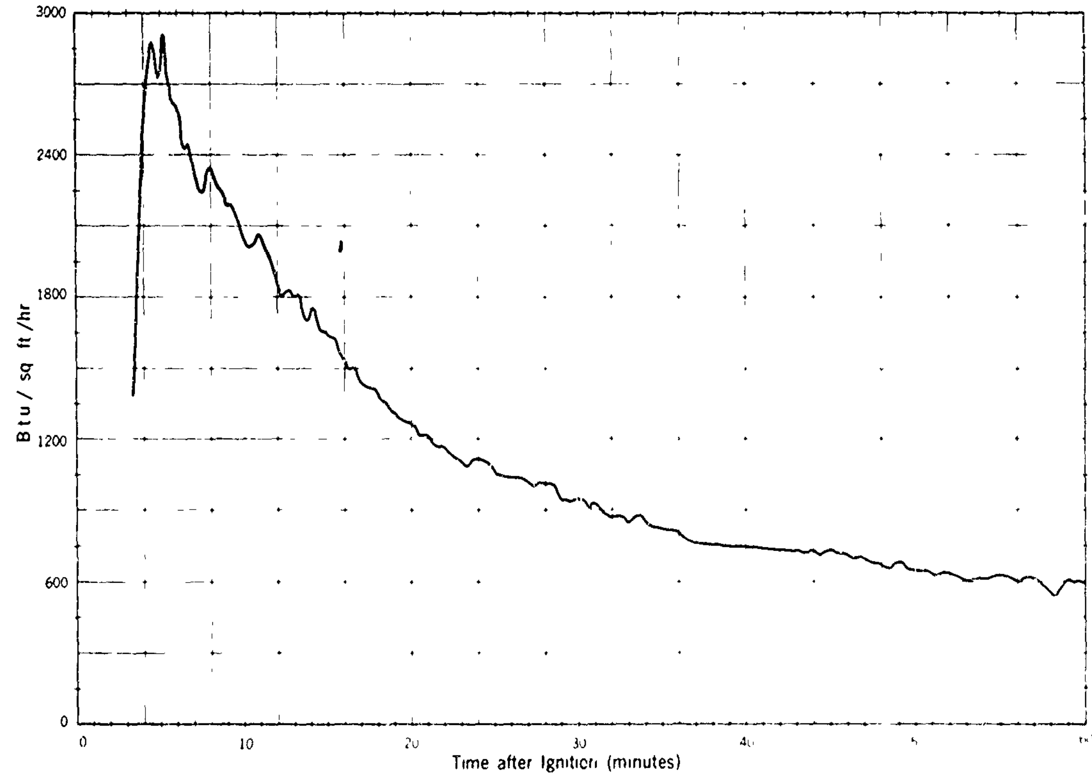


Figure 50–*Thermal radiation at location B, Test Fire 5, June 14, 1966.*

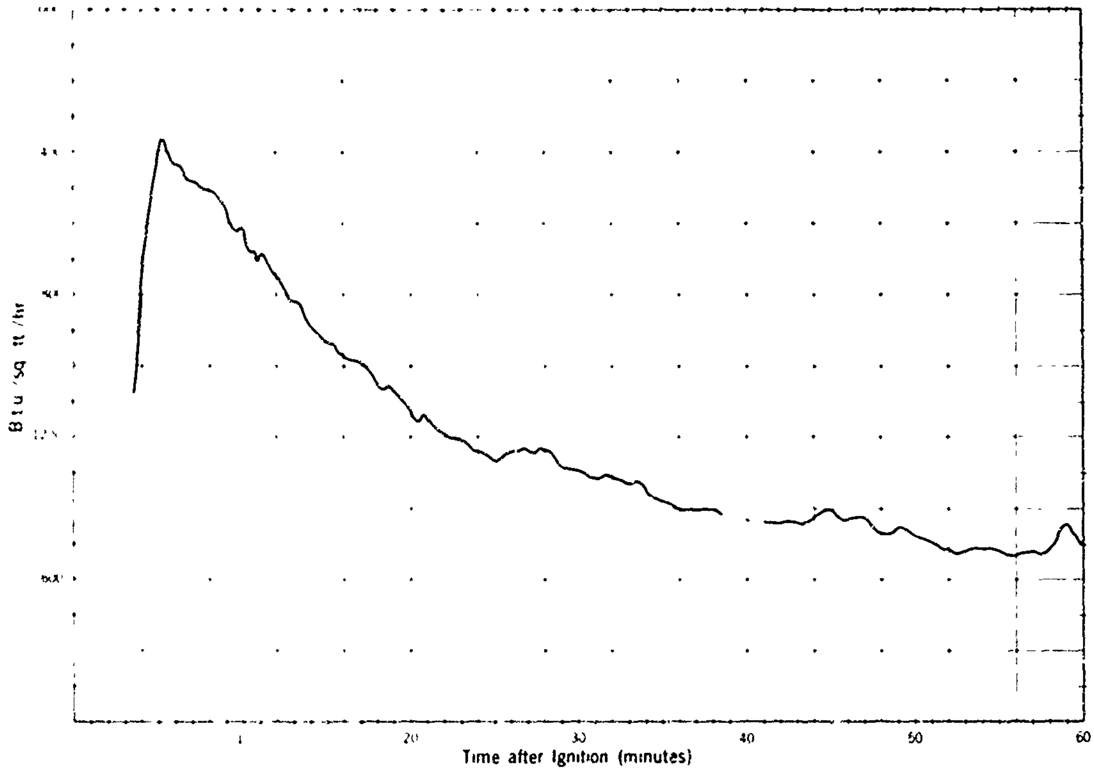


Figure 51--*Thermal radiation at location C, Test Fire 5, June 14, 1966.*

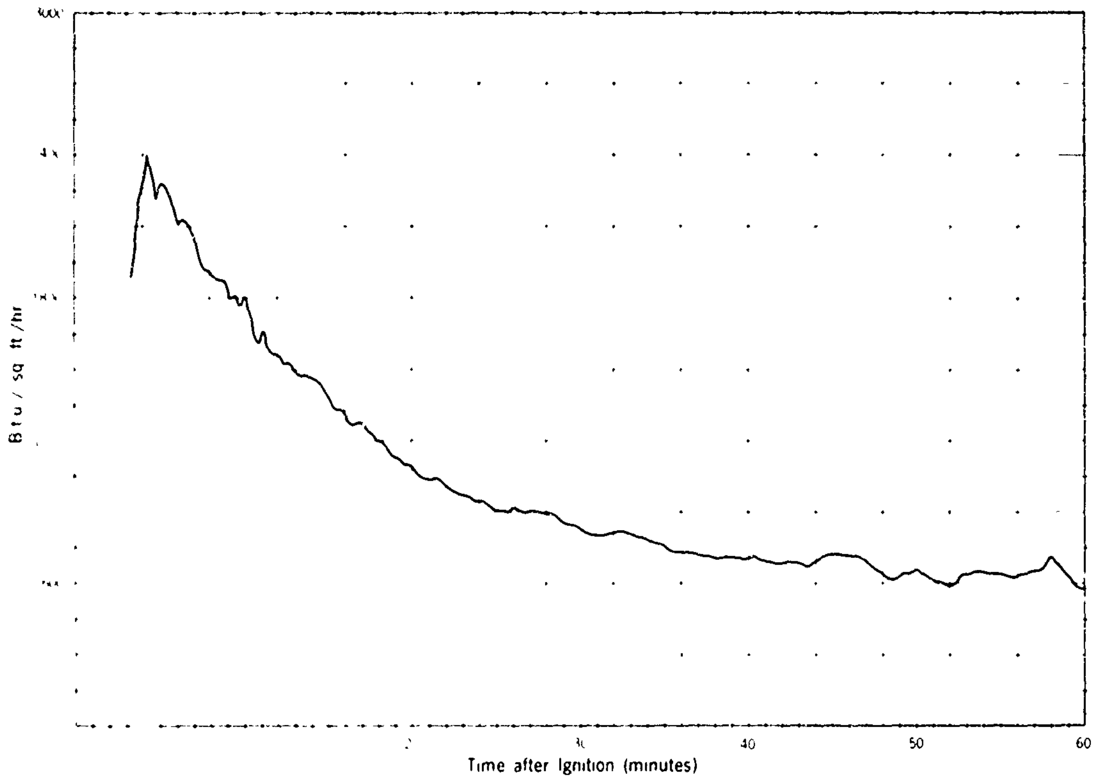


Figure 52-*Thermal radiation at location D, Test Fire 5, June 14, 1966.*

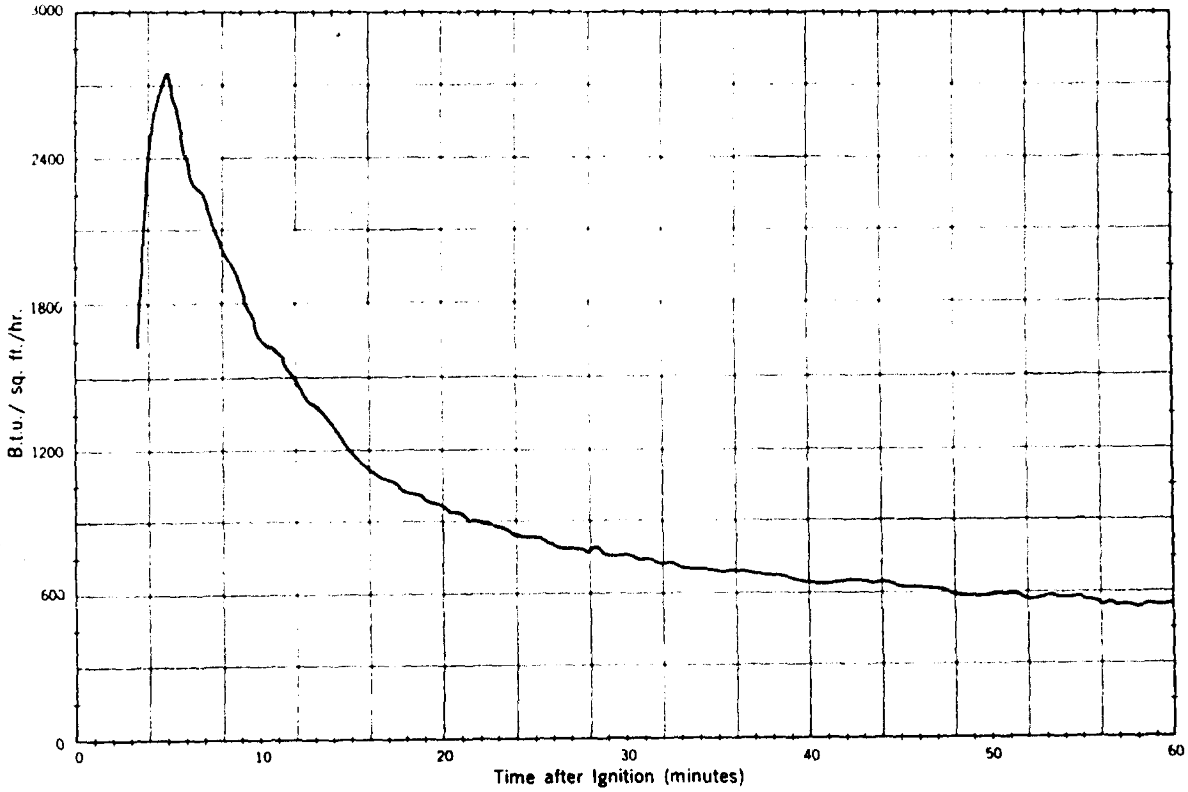


Figure 53—*Thermal radiation at location E, Test Fire 5, June 14, 1966.*

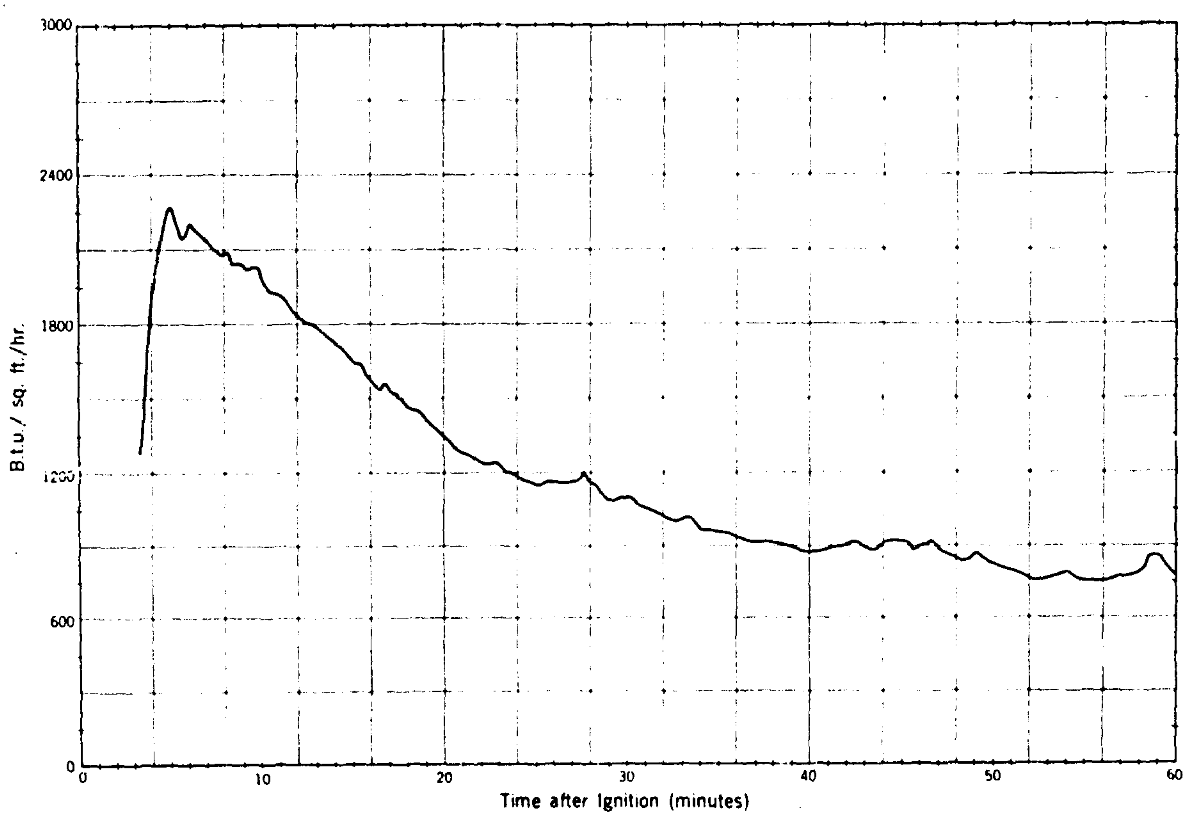


Figure 54—*Thermal radiation at location A, Test Fire 5, June 14, 1966.*

fire center line than nearer the fire edges. As the fire progressed air inflow decreased and smoke obscuration lessened. The thermal radiation rate at the center location was then higher than that at the corner locations. The relative radiation rates then more nearly approached that which would be expected from a uniform fire area.

The high peak radiation rate at location B is also the result of fire behavior. The sector of the fire viewed from this location built up rapidly and appeared to burn more intensely than other areas in the fire possibly because of differences in the fuel bed loading. The fuel beds burned out quickly, and the rapid decline in fire activity is apparent in the radiometer record.

Because of natural variations the fuel beds do not burn uniformly, neither within fuel beds nor between fuel beds. This variation in burning rate causes most of the minor variations appearing in the radiation records. The larger "bumps" in the records, however, could well be caused by fire whirls which locally increase flaming for short periods. Possible fire whirl effects are particularly apparent in the last half of the radiation record for location C *(fig. 51)*.

On the fire flank (location E) the peak radiation (2,754 Btu/ ft.^{2}/hr.) was only slightly lower than at location B. And the radiation pattern was similar at both locations *(fig. 53)*. Location E was upwind from the strong inflow area on the fire flank and apparently was little affected by it. Fire whirls did not develop on this side of the fire, and the radiation rate curve is relatively smooth.

Except for a lower radiation level, the radiation pattern at location A, 200 feet from the fire edge, is nearly identical to that from location C *(fig. 54)*. Fire whirl effect was also apparent at this location.

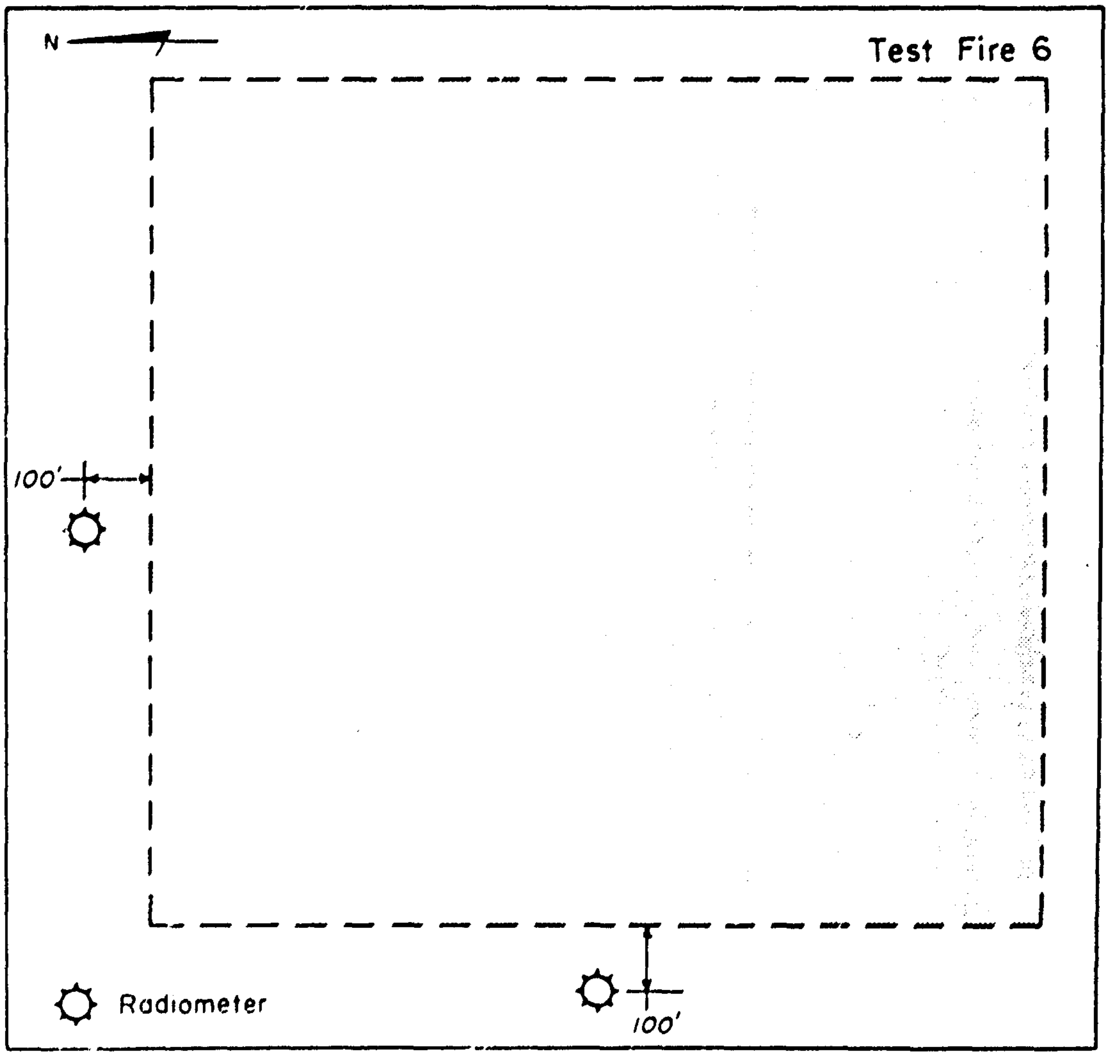


Figure 55 *Radiometers in Test Fire 6, September 29, 1967, were set up on the west and south sides.*

For Test Fire 6, radiometers were placed near the center lines on the west and north sides of the plot *(fig. 55)*, at 10 feet and 50 feet above the ground, and 100 feet from the fire edge. Ambient wind was from the southwest at approximately twice the speed in Test Fire 5. Because of numerous unseasonable rains the fuel moisture for Test Fire 6 was about double that for Test Fire 5, averaging 12 percent or more for most fuel element sizes.

At the 100 foot level on the west side, the thermal pulse indicated by the radiometer in Test Fire 6 was quite different than in Test Fire 5. Rising more slowly, radiation rates did not show a sharp initial peak *(fig. 56)*. The peak rate–reached about 12 minutes after ignition at 1,300 Btu/ft.^{2}/hr.–was about one-half the rate in Test Fire 5. From this side of the fire the thermal pulse shape appeared to be between that of Test Fire 4 *(fig. 10)*, burned under high moisture conditions, and that of Test Fire 5, in which fuels were quite dry.

The thermal pulse at the 50-foot level *(fig. 57)* at the west location resembled that at the 10-foot level, except for higher radiation rates. Since at the 50-foot level more of the fire area was within the view angle of the radiometer, this higher rate could be expected.

The radiation curve at the 10-foot level on the north side of the fire *(fig. 58)* was somewhat different than on the west. The peak rate was reached earlier–about 5 minutes after ignition. And it was much higher, reaching a value of 2,400 Btu/ft.^{2}/hr. As with the curve recorded on the west side, the radiation curve at 50 feet *(fig. 59)* was similar to that at the 10-foot level, but with a higher radiation reading.

At both the 10- and 50-foot levels, the radiation curves obtained for the north side were more erratic than those from the west. Numerous "peaks" and "valleys" are apparent. Effects of wind and fire whirls were probably responsible for this difference. On the west side, the ambient wind coupled with the fire-induced indraft kept the flames leaning strongly into the fire in the first two rows of fuel beds. Beyond this, much of the fire was obscured by smoke, particularly in the early part of the fire. On the north side the flames were more upright, and there was considerably less smoke obscuration at low levels. Because of the wind, however, the convection column was strongly tilted toward the radiometer location. And convective heat sometimes reached the radiometers, particularly at the 50-foot level. The turbulent wind flow in this area resulted in intermittent, partial, obscuration of the fire by smoke.

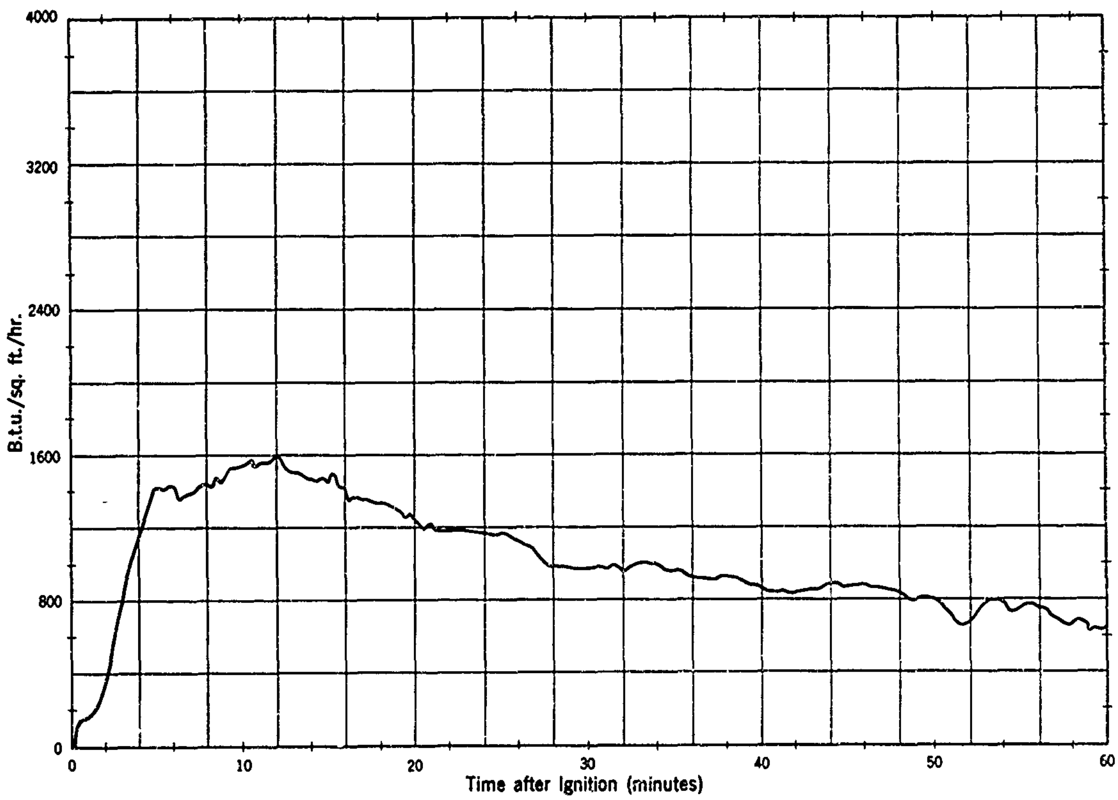


Figure 56–*Thermal radiation at the 10 ft. level, west side of Test Fire 6, September 29, 1967.*

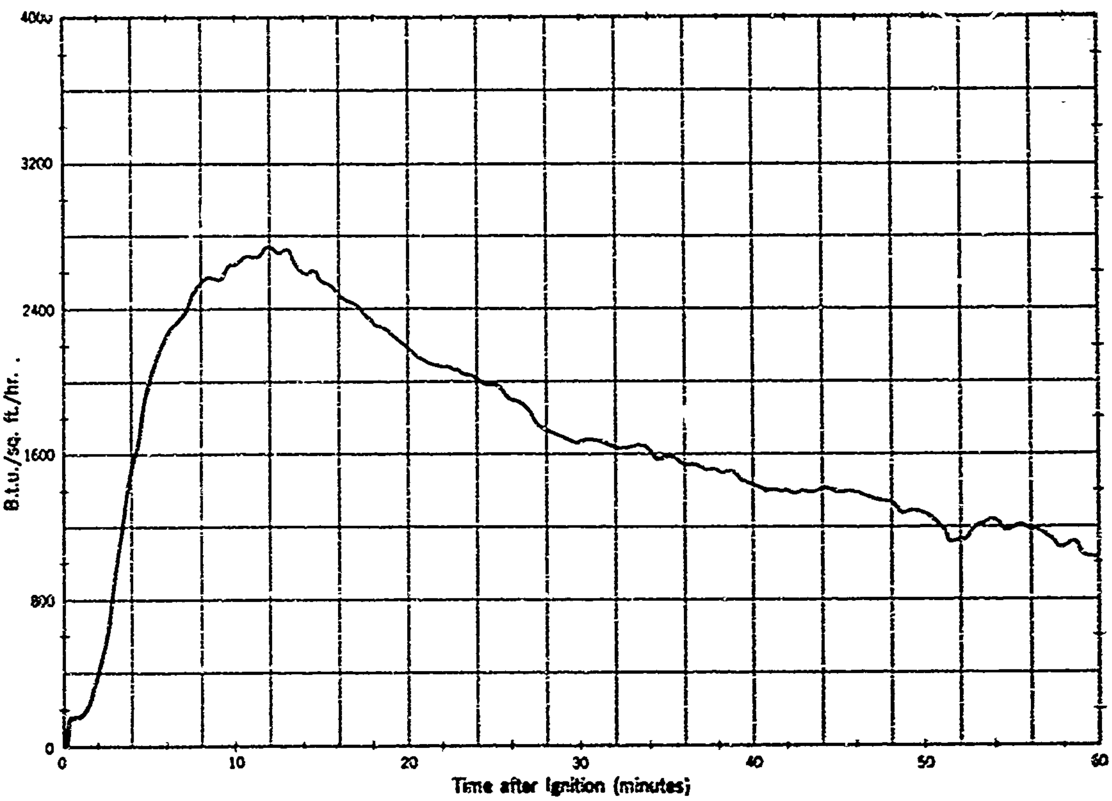


Figure 57–*Thermal radiation at the 50 ft. level, west side of Test Fire 6 September 29, 1967.*

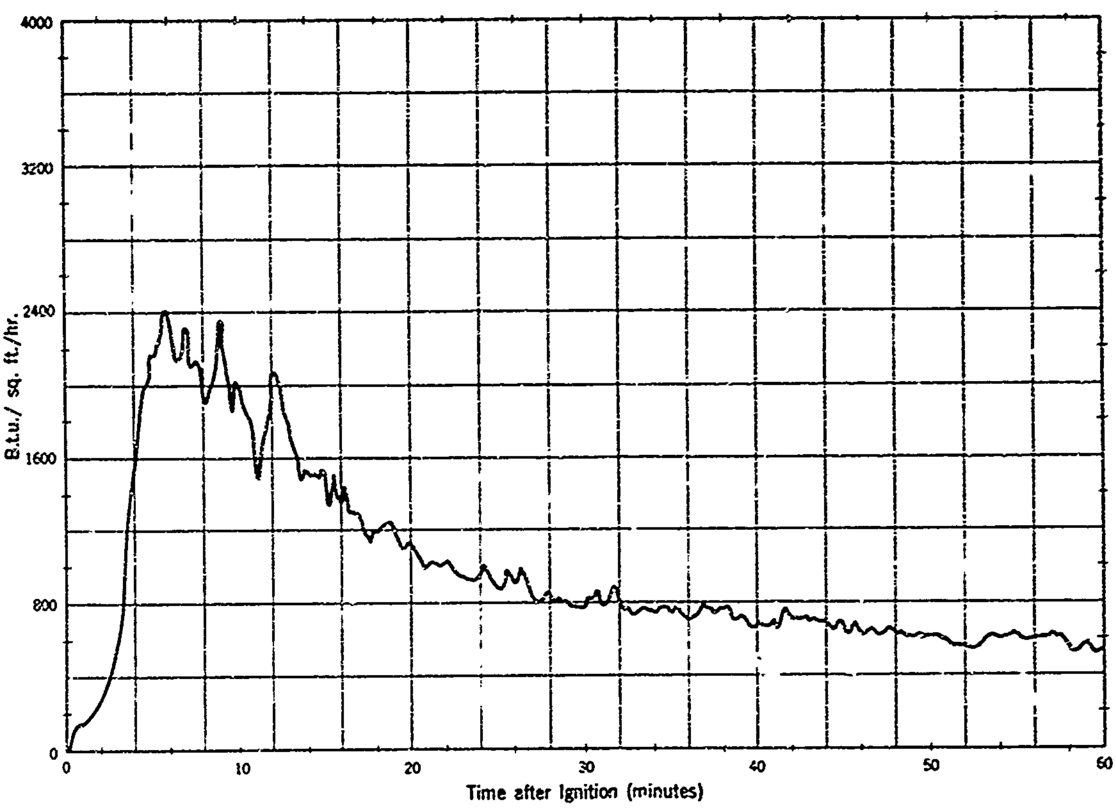


Figure 58–*Thermal radiation at the 10-ft. level, north side of Test Fire 6, September 29, 1967.*

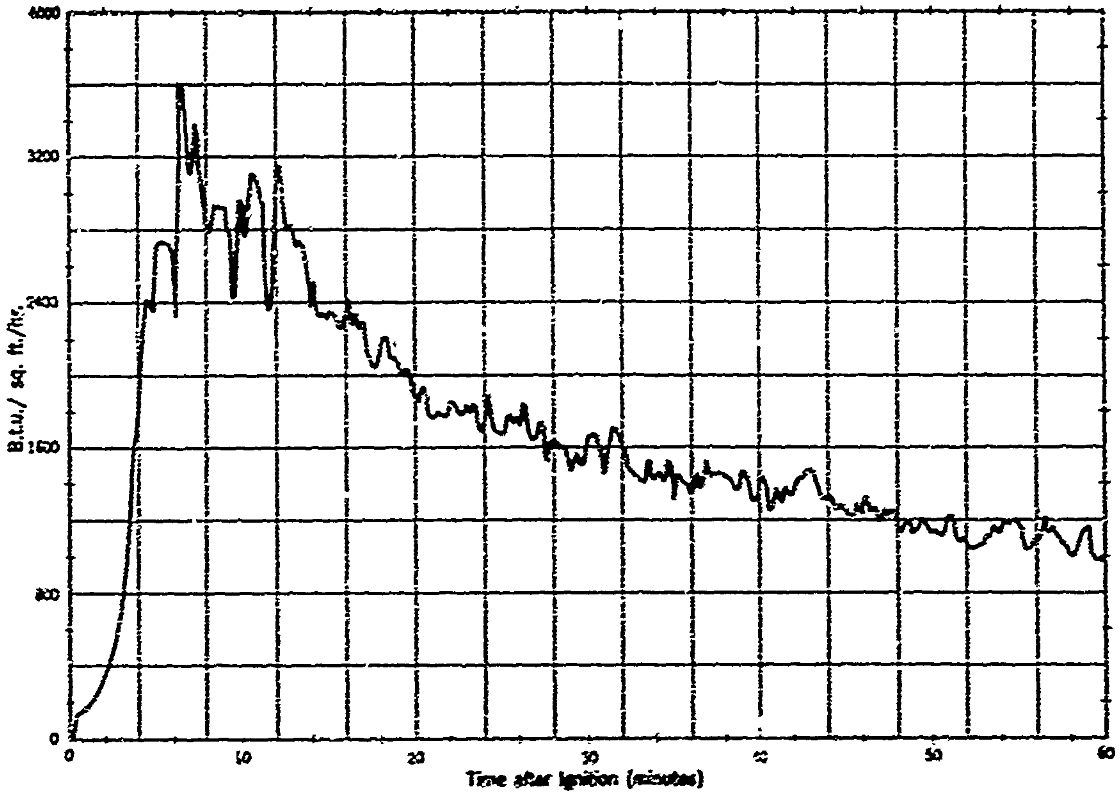


Figure 59—Thermal radiation at the 50-ft. level, north side of Test Fire 6, September 19, 1967.

Fire whirls began developing early in the fire near the north edge and within the view of the radiometer. They probably contributed greatly to the fluctuating radiation from the north side. From the west side the whirls could not be seen by the radiometer until late in the fire because of the dense smoke.

Ignition

In all the test fires, we found that ignition of ground-level fuels outside of the plot area was confined to a short distance from the fire edge. On the windward side and flanks this distance was nearly always less than 10 feet. On the lee side the distance varied, and appeared to depend on flame angle and on flame length. This distance was never observed to exceed the vertical projection of the flame to the ground.

In one of the test fires (380-6) of fire-killed timber fuels, thermocouples were inserted into hardwood dowels 1/4-inch in diameter and 4-inches long. The thermocouples were in the center of the dowel radially and about 1 inch from the upper end. The dowels were exposed in an upright position about 24 inches above the ground and at various distances from the fire edge. The highest temperature recorded was only 295°F. in a dowel 6 feet from the fire edge even though flame heights reached 50 to 60 feet, and a hot fire persisted for several hours. The temperature-time curve *(fig. 60)* for the dowels closely resembles the thermal pulse given by a flat plate radiometer *(fig. 61)* for the same fire.

The cooling effect of ambient and convective air flow is probably responsible for the low temperature in materials adjacent to the fire area. Around the single-fuel bed tests the exposed fuels were usually small and generally well exposed to the air flow.

The restricted area of ignition by radiation was also observed in the multiple fuel bed fires. In Test Fire 6, the ignitors in two fuel beds in an outside row failed. Four fuel beds outside the plot were purposely left without ignitors. None of these fuel beds ignited during the fire despite other burning fuel beds only 25 feet away. We also noted that on the windward side and flanks of this and other multiple-fuel-bed fires, the grass, brush, and twigs in the "streets" oriented in the direction of air flow did not burn for a distance of 75 feet or more into the fire interior. In addition, vegetation in some areas well within the interior of the fire also was not burned.

Wildland fuel beds in their natural state are quite porous. The fuels outside the fire are readily cooled by air flow and radiant heating, thus making radiant

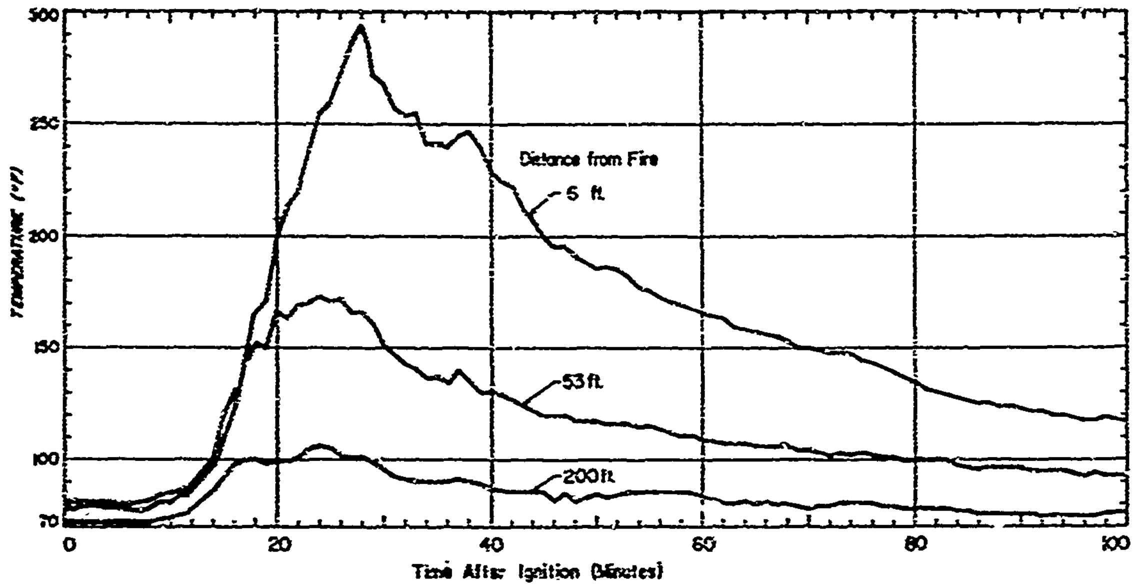


Figure 60–*Relation of time to temperature in wood dowels holding thermocouples at various distances from the edge of Test Fire 380-6.*

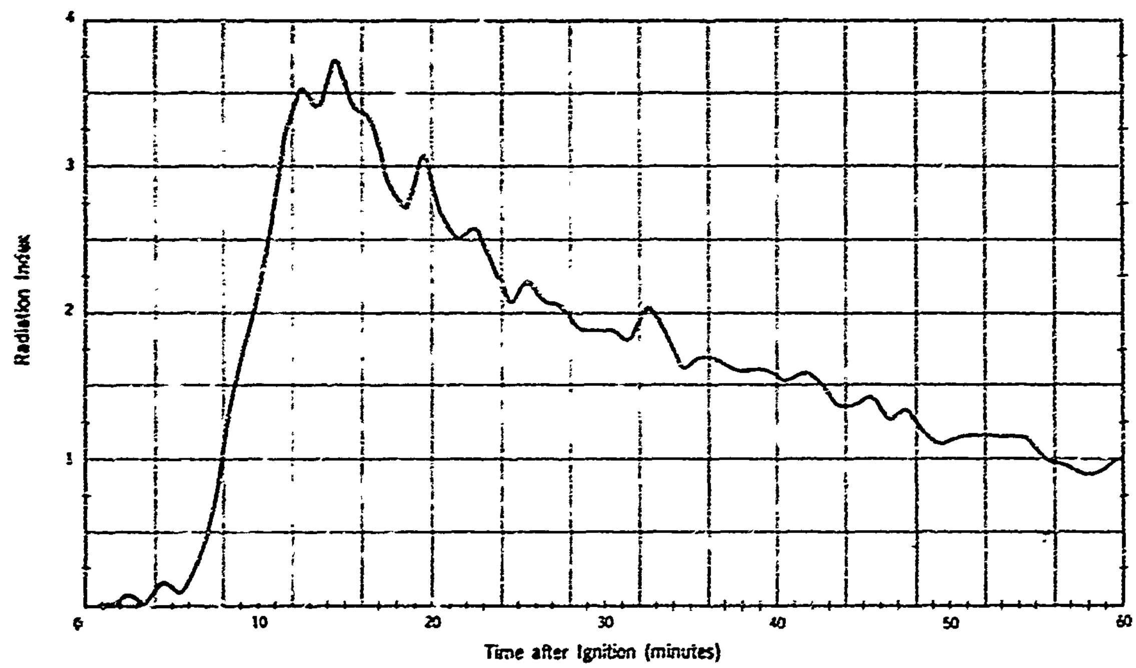


Figure 61–*Thermal radiation in Test Fire 380-6.*

heating of fuel ahead of a fire a relatively slow process. It is unlikely that radiation is a major factor in spread of fire in wildland fuels except under special conditions, such as very low ambient wind speeds, or in very narrow, steep-sided canyons.

In urban fires, radiation may be a more vital factor in fire spread. The extensive flat surfaces of buildings give greater exposure to radiant heating and provide for less effective cooling by air flow. But evidence suggests that in urban centers wind and flying fire brands are the key factors in spreading fire. Storey and Noel (1965) have compiled a list of major urban fires for the period 1925 to 1965. In most cases where the reason for fire spread was available, wind

effects and spotting were given as the major causes of fire spread.

Mass Loss Rates

One use of radiation data from fires has been in estimating the mass loss rates of the burning fuel. Lack of data on actual mass loss rates for field-scale fires has made the validity of such estimates open to question. The milled-fuel-bed fire (6A) and smaller crib fires used in the development of the mass loss rate experiment set up in Test Fire 6 provided an opportunity to explore this question since both mass loss rates and thermal radiation data were recorded.

Crib Fire B described earlier, contained four of the 6- by 6-foot modules. One ignitor in the center of the four modules provided ignition. In this fire a flat plate radiometer was exposed 3.5 feet above the top of weighing platform and 21 feet from the edge of the fuel bed. Weight loss and radiation were recorded continuously.

Based on the total mass loss and thermal radiation for the first 30 minutes of the fire, mass loss and radiation rates were computed in percent per minute. Plotted over time, they showed a similar form *(fig. 62)*, although the radiation peak was reached somewhat later than the peak mass loss rate.

In crib Fire 6A the radiometer was exposed 10 feet above the top of the weighing platform and 50 feet from the edge of the fuel bed. This fire contained 49 of the 6- by 6-foot modules and was ignited by six evenly spaced ignitors. In the early stages the mass loss rates differed from the radiation rates. The mass loss rate peaked quickly and then declined immediately; the radiation rate had a much broader peak that did not reach its highest point until the mass loss rate had declined to nearly half of its peak value *(fig. 63)*.

To provide a better comparison of mass loss and radiation rates the ratio of the average radiation rate during a given time period to the mass loss rate during the same period was computed. If mass loss rates and radiant energy incident on the radiometer are directly related, then this ratio could be expected to be constant. The ratios, however, showed a considerable deviation from a constant value *(fig. 64)*.

There are several reasons for this disparity. A radiometer responds only to the radiation from the surface within its view angle—on what the radiometer "sees." In the ignition stage of the fire, much of the burning takes place within the fuel bed, and flames are relatively low. Therefore, fuels shield the radiometer from much of the combustion area, and the radiation-mass loss ratio is small. Generally, the lower the radiometer in relation to the fuel bed the greater the shielding will be in the first stage of the fire.

As more fuel is involved in the initial combustion stage, more flammable gas is produced than can burn within the fuel bed. Much of the combustion then

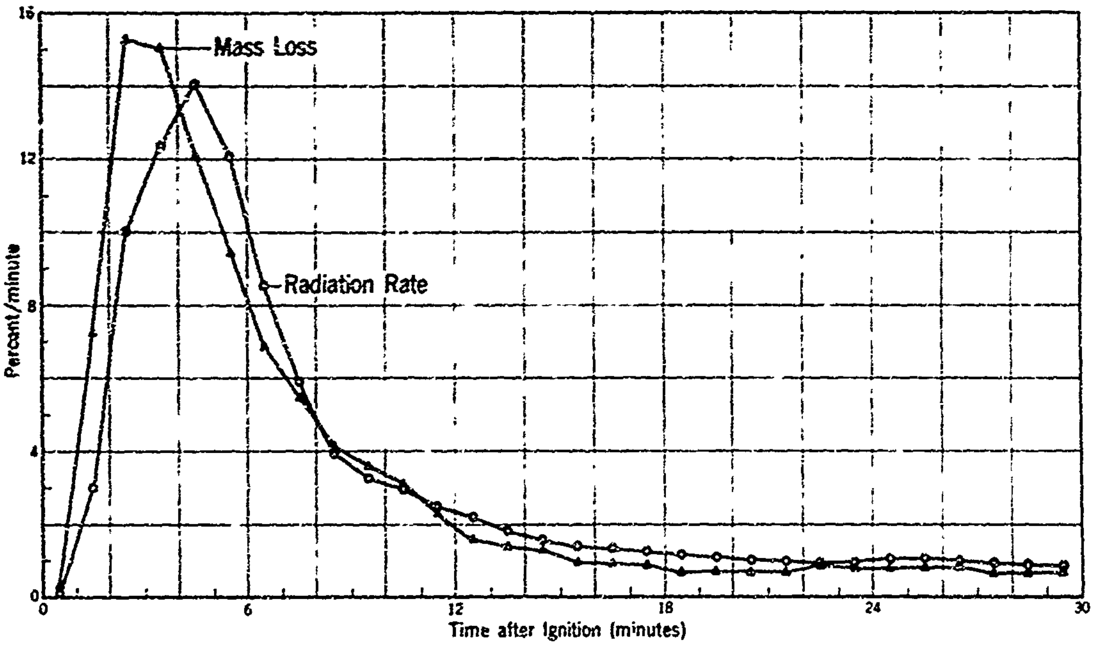


Figure 62—*Mass loss and thermal radiation rates were similar in Crib Fire B.*

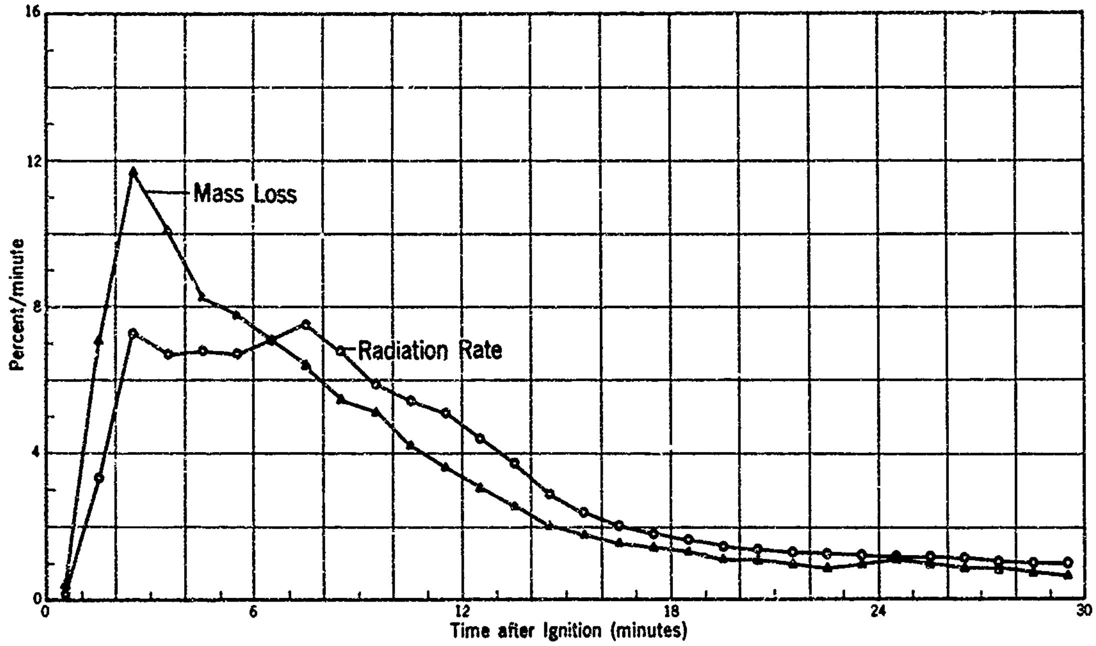


Figure 63–*Rate of mass loss had a higher peak than did the thermal radiation rate in Test Fire 6A.*

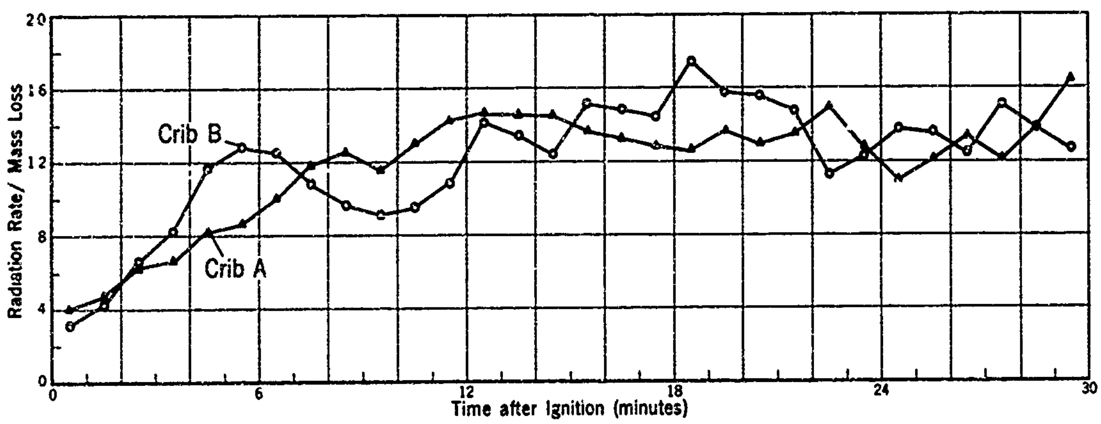


Figure 64–*Ratio of radiation rate to mass loss rate in Crib Fire B, and Test Fire 6A.*

takes place above the fuel bed, and within the view of the radiometer. Peak flame heights and maximum mass loss rates occur during this stage. And the flame shape usually is in the form of a truncated cone or sometimes roughly cylindrical in shape *(fig. 65).* Flame volume is thus relatively large as compared with surface area.

As the fuel moves into the second and third combustion stages the volume of flammable gas production decreases. Flame shape also changes–frequently assuming a conical shape, or the burning area may consist of a number of cone-shaped flames *(fig. 66).* Surface area of the flame then becomes larger compared with volume than in the initial stage of the fire and hence, produces a larger radiation output relative to the mass loss rate *(fig. 64).*

As the fuel combustion proceeds into its third stage the proportion of charcoal to unburned wood increases. Since charcoal has nearly twice the heat of combustion per unit weight as wood the amount of heat produced per unit of mass loss also becomes greater. This difference also contributed to the higher radiation-mass loss ratios in the later stages of a fire.

The efficiency of combustion also affects the relationship between mass loss rates and radiation. In the early stages of a fire, volatile gas production rate

Figure 65—*In early stages of a large fire, the flames may turn cylindrical in shape. Flame heights reach a peak and mass loss rates are at a maximum.*

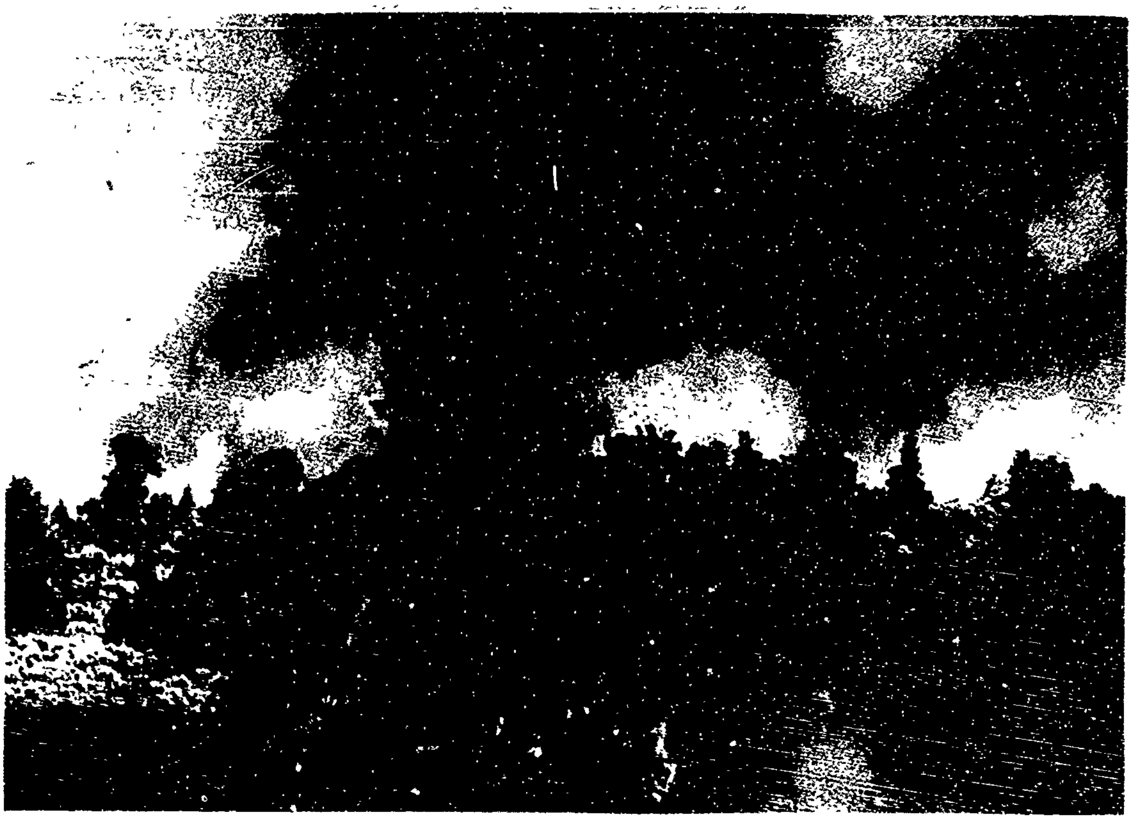


Figure 66—*In middle stages of a large fire, the flames are cone-shaped. Volume of flammable gases decrease.*

is high. And some gases likely escape without being burned. Much solid particulate matter is produced, as evidenced by the much denser and dark smoke produced. Therefore, efficiency of combustion in the early fire stages is less than in the later, less violent burning stages. This difference would also tend to increase the radiation-mass loss ratio as the fire progresses.

From the results of the Flambeau test fires it appears that thermal radiation has been overated as a factor in fire spread when there is significant air flow. But in light winds, slow spreading fires, and certain topographic situations, radiation may assume a more important role in fire propagation.

The relationship between thermal radiation rates, as measured by a wide-angle radiometer at one point, and mass loss rate of burning fuel is not close. When a fire is burning violently the mass loss rates are probably closely associated with the volume of flame produced; the radiation rate, on the other hand, depends on the surface area of the flames. Thus, flame shape assumes significant importance in this relationship.

Flame shape changes with time as combustion of the fuel bed proceeds. It may also be altered by ambient air flow and turbulence induced by the fire. Thus, the amount of radiant heat a receptor may receive depends upon the burning characteristics of a given fuel bed, external conditions that may alter the burning characteristics, and receptor position with respect to the fire.

Although thermal radiation may not be a primary factor in fire spread it is of major importance in defense of civilians. In Test Fire 1, the fuel beds were spaced 115 feet apart. Air temperature at 4.5 feet above the ground reached a peak of 65°F. (24° above ambient) in 60 to 90 seconds. Despite the low air temperature, however, the radiated heat made it impossible for unprotected personnel to walk between the fuel beds during the violent flaming period--about 12 to 15 minutes.

In the fires with close-spaced fuel beds a 150-foot distance from the fire was the limit of human tolerance during the peak flaming period, although short-time exposure at a closer distance was possible. As the fuel was consumed the limiting distance became less and less, and it was usually possible to walk between the fuel beds after 60 to 90 minutes. Thus, although radiant energy levels were not high enough to ignite fuel more than a short distance from the fire the radiation level outside the fire area was above the limit of human tolerance for a significant period of time.

Temperature

Of all the parameters measured, temperature was the most difficult to obtain in large fires. The amount of data obtained in Flambeau tests was limited by difficulties created by high and variable temperature, long thermocouple leads, electrical noise generated or intensified by the fire, and mechanical failure of thermocouples and supports in the hostile environment, along with the relatively small amount of instrumentation. But enough data were obtained to indicate the magnitude of temperature to be expected and some of the factors that may affect the temperature in mass fire.

Fuel Zone Temperature

Milled fuel beds used varied in size from 4- by 4- by 4-inches to 42-feet by 42-feet by 64-inches. Peak temperature within these fuel beds did not appear to vary with the size of the bed. Peak temperatures ranging from about 1,900°F. to 2,500°F. were measured in both the small and large fuel beds. Porosity of these fuel beds was low enough to severely restrict the air inflow to the fuel bed interior. The fuel bed porosity increased as the fuel was consumed, thus permitting more ambient air to penetrate to the fuel bed interior. Rate of decline of temperature from its peak was closely associated with the extent of "opening up" of the fuel bed. Temperatures measured over wildland fuel beds were in the same order of magnitude as those over crib fires. Thus the peak temperatures for the wildland fuel beds probably fall within the same range as those for milled fuels.

Flame Zone Temperature

A persistent characteristic of flame temperatures above a burning fuel bed is their large and rapid fluctuations. This fluctuation occurred in single fuel-bed fires (Countryman 1964) as well as those in multiple array. An example of this fluctuation is shown in a recorder trace of a platinum-platimun-rhodium thermocouple exposed 10 feet above a wildland fuel bed in Test Fire 5 *(fig. 67)*. The recorder had a full-scale response time of 0.125 second. Turbulent air flow mixing cooler ambient air with the flames and gases above the fuel bed and flame pulsing or "flicker" probably accounted for most of this fluctuation.

Peak temperatures in the combustion zone vary over a wide range and seem to be related in part to rate of combustion. Fuel beds in Test Fire 2 burned more violently than those in the other test plots. In this fire the flames above the fuel beds were massive

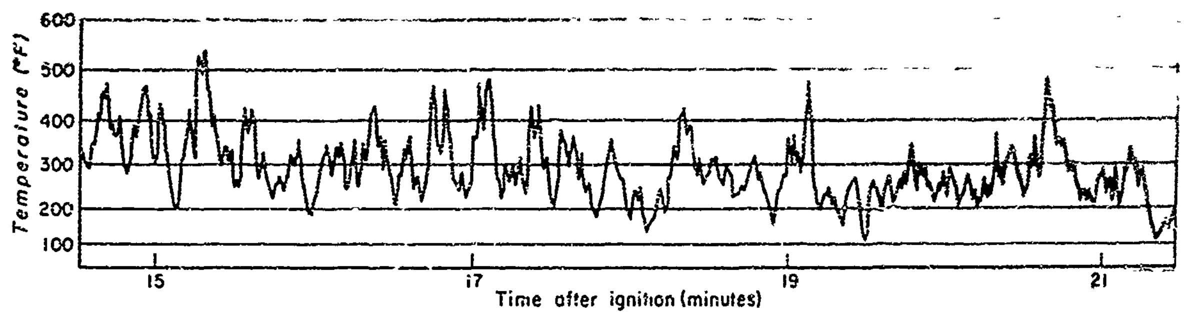


Figure 67–*Thermocouple trace, Test Fire 5, June 14, 1966. Shows flame temperature fluctuations, by time after ignition.*

and extremely turbulent. Ring vortices composed entirely of flame often formed just above the fuel bed. And flame temperatures apparently went higher than the limit (2,500°F.) of the chromel-alumel thermocouples exposed over the fuel beds. They may have exceeded 3,000°F. (Philpot 1965). Similar flame activity also appeared in one of the milled-fuel fires burned individually. At 10 feet above the fuel bed the temperature exceeded the limit of the chromel-alumel thermocouple. Peak temperature within the fuel bed, however, was 2,300°F. With less violent burning, such as occurred in Test Fires 5 and 6, and in other crib fires, the massive flames and extreme turbulence were less pronounced. Peak temperatures 10 feet above the fuel bed in these fires ranged from 1,600°F. to 1,900°F.

It is not certain whether the higher flame zone temperatures in the fires with the faster combustion rate is due to less cooling by ambient air mixing or to a better gas-air mixture. Appearance of the flames suggests the latter may be a more likely explanation. In the violently burning fires the masses of burning gas often assumed a bright orange color indicative of high temperature and efficient combustion. In the less violent fires the flames tended to be dull red.

Gas Temperature

In most of the multiple-fuel-bed fires, temperature was measured in the spaces between the fuel beds and also above the combustion zone. Temperature between the fuel beds varied widely with time and with height above the ground (Countryman 1964; Philpot 1965). In one plot with wide fuel-bed spacing, the air temperature at 4.5 feet rose only by 24°F. (Countryman 1964). In the close-spaced fuel-bed fires, the flames often filled the spaces between the fuel beds, and temperatures approached flame temperature.

Temperatures were recorded by shielded and aspirated chromel-alumel thermocouples at a tower 12.5 feet from the center milled-fuel bed 1 during the first 6 minutes of Test Fire 6 *(table 5)*. Peak temperatures probably were not reached by the 6-minute mark; however, the collapse of another tower elsewhere in the fire partially opened the aspiration system and made later temperature measurements dubious. Even though temperatures may have actually been greater, the temperature of more than 1,100°F. at 3.5 feet indicates the potential protection needs for civil defense.

Temperatures above the combustion zone usually decrease rapidly with height—at least through the transition zone. In the first 6 minutes of Test Fire 6, the temperature at 100 feet above the center of milled-fuel bed 1 rose to 640°F. The flames over this fuel bed were probably 50 to 60 feet tall at this time, and the temperature within the fuel bed in the order of 2,500°F. Only 75 feet away a thermocouple suspended 40 feet above the weighed wildland fuel bed indicated a maximum temperature of 660°F. *(fig. 68)*. This peak temperature occurred at the same time weight loss rate was at maximum and when peak flame heights can be expected. Flames probably did not exceed 30 feet and probably were pulled toward the stronger fire in the adjacent milled-fuel bed.

Temperature within a fire system is marked by

Table 5–*Temperature profile for Test Fire 6 (760-12-67), September 29, 1967*

Time[1]	Height above ground (ft.) . . . 3.5	7	20	50	80	100
	Degrees F.					
1:13	130	150	180	110	80	80
2:12	230	250	690	400	280	220
3:11	1010	1030	870	230	230	240
4:10	980	970	360	340	270	400
5:08	1000	850	760	360	360	250
6:08	1120	1020	510	1160	960	640

[1]Minutes and seconds after ignition.

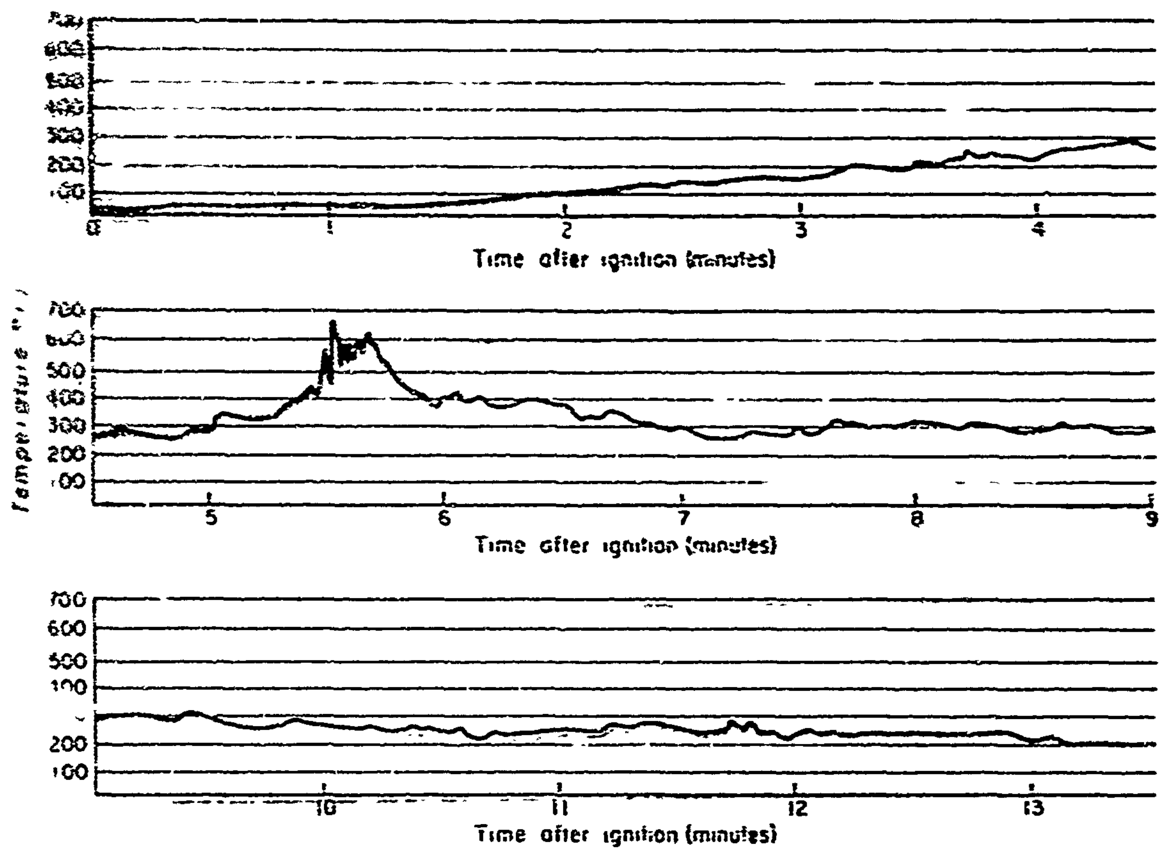


Figure 68—*Thermocouple trace in Test Fire 6, September 29, 1967, shows fluctuations in temperature, by time after ignition.*

wide spatial and temporal variations. These variations seem caused by the entrainment of ambient air into the fire area and the strong turbulence within the fire system.

Peak temperatures within Flambeau fuel beds ranged from 1,900°F. to 2,500°F. Size of these fuel beds appeared to have little effect on the internal temperature; however, the beds were all of about the same porosity. Because of the effect of ambient air on temperature, fuel beds of other characteristics may give different peak temperatures.

Variation of temperature in the combustion zone of a fire system is strongly affected by the air turbulence and is also related to the combustion rate. Under favorable conditions peak temperatures may be near the maximum (estimated to be 3,500°F.) possible for wood-derived gases. The necessary conditions were approached in some Flambeau fires. These higher temperatures did not seem to affect the temperature of the interior of Flambeau fuel beds—possibly because of the generally short duration of the massive gas production needed to produce high temperature.

Air flow patterns and turbulent mixing also affect temperature variations in areas outside the active combustion zone but within the fire. Above the combustion zone, temperature tends to drop rapidly with height. Because of inflowing air, little temperature increase can be expected outside the fire boundaries.

Noxious Gases

Increasing concern has been expressed over the role that noxious gases may play in the safety and actions of personnel in and around a fire area. In World War II, many people that died in shelters were apparently untouched by fire. Even in areas subject to high temperature, the position of bodies and the mein of the victims indicated that death was often not from burns but from some other cause. The same conclusion has been reached in some cases in which firefighters have been killed in wildland fires.

To find out if gas could be responsible for such fatalities, we took samples in and around many of the Flambeau test fires. In the early fires, analyses were

confined to carbon monoxide, carbon dioxide, and oxygen. In the later fires, oxides of nitrogen, hydrocarbons, water vapor, and particulate matter were also sampled. Results of these analyses were reported by Bush, Leonard, and Yundt (1969).

In general, gas samples taken in or near the combustion zone have showed a concentration-time pattern quite similar to the thermal pulse pattern. For noxious gases, peak concentrations occurred early in the fire at about the same time as peak flaming and mass loss. Then came a long period of low but sometimes significant concentration of hazardous gases. The oxygen concentration followed the inverse of this pattern—minimum concentration occurred early in the fire and little oxygen deficiency was apparent in the later stages. Thus, peak concentrations of noxious gases, maximum water vapor concentration, maximum oxygen, and maximum heat all occurred at about the same time.

The precise effect of various concentrations of carbon monoxide on humans is not known with certainty. Tolerance varies among different people. And the carbon monoxide effects seem to vary with the degree of activity of the subject. Synergistic effects of noxious gases produced by combustion in combination with heat is particularly uncertain. But some progress toward an understanding of these effects is being made (Pryor, Fear, and Wheeler 1968).

Table 6–*Effects of carbon monoxide on humans*

Carbon monoxide content of inhaled air (percent)	Effects
0.02	Possible mild frontal headache after 2 to 3 hours.
0.04	Frontal headache and nausea after 1 to 2 hours. Occipital (rear of head) headache after 2½ to 3½ hours.
0.08	Headache, dizziness and nausea in ¾ hour. Collapse, unconsciousness and possible death in 2 hours.
0.16	Headache, dizziness and nausea in 20 minutes. Collapse, unconsciousness and possible death in 2 hours.
0.32	Headache and dizziness in 5 to 10 minutes, unconsciousness and danger of death in 30 minutes.
0.64	Headache and dizziness in 1 to 2 minutes, unconsciousness and danger of death in 10 to 15 minutes.
1.28	Immediate effect. Unconsciousness and danger of death in 1 to 3 minutes.

In clinical tests Claudy (1954) observed the physical effects on victims exposed to an atmosphere containing carbon monoxide. The effects ranged from mild headaches to a lethal exposure *(table 6)*.

From information compiled by Sollman (1948), Broido and McMasters (1960) have prepared tables showing the effects of carbon dioxide and oxygen deficiency *(tables 7, 8)*.

Continuous samples of gases have indicated peak carbon monoxide concentrations exceeding 1 percent in several test fires. Grab samples have indicated the concentration may exceed 5 percent in some areas. Carbon dioxide concentrations exceeding 10 percent have been measured in some of the last Flambeau fires, and oxygen concentrations have dropped below 7 percent.

Table 7–*Effects of oxygen deficiency on humans*

Oxygen content of inhaled air (percent)	Effects
20.9	No effects; normal air.
15	No immediate effect.
10	Dizziness; shortness of breath; deeper and more rapid respiration; quickened pulse, especially on exertion.
7	Stupor sets in.
5	Minimal concentration compatible with life.
2-3	Death within one minute.

Table 8–*Effects of carbon dioxide (oxygen content normal) on humans*

Carbon dioxide content of inhaled air (percent)	Effects
0.04	No effects; normal air.
2.0	Breathing deeper; tidal volume increased 30%.
4.0	Breathing much deeper; rate slightly quickened; considerable discomfort.
4.5-5	Breathing extremely labored, almost unbearable for many individuals. Nausea may occur.
7-9	Limit of tolerance.
10-11	Inability to coordinate; unconsciousness in about 10 minutes.
15-20	Symptoms increase, but probably not fatal in 1 hour.
25-30	Diminished respiration; fall of blood pressure; coma; loss of reflexes; anesthesia. Gradual death after some hours.

Results of the noxious gas investigations in the test fires served to confirm that noxious gases can be a very real hazard to civilian populations and to firefighters. Concentrations of carbon monoxide in particular, can occur in lethal concentrations both in and near a fire area. The hazard is intensified by noxious gases and water vapor to reach peak concentration at the same time as minimum oxygen and maximum heat.

Of significance also was the long period of relatively low concentration (0.05 percent or less) of carbon monoxide. Beard and Wertheim (1967) found that human judgment was significantly impaired when subjects were exposed to an atmosphere containing 50 parts per million (0.005 percent) for 90 minutes. The time required for significant impairment of judgment decreased rapidly with increasing concentration, and at 250 parts per million (0.025 percent) was only about 22 minutes. Carbon monoxide concentrations of these orders of magnitude apparently can persist in a fire area for several hours. Near the center of Test Fire 6, for example, the concentration of carbon monoxide at 0.05 and 5 feet above the ground in the center of a "street" was still 0.02 percent or greater when sampling was discontinued 4 hours after ignition. This situation may not be important in a small fire where people may escape quickly and exposure time is likely to be short. But it can become critical in a very large fire, such as might be expected from a nuclear attack, where people may have to remain in the fire area for extended periods.

Fire Whirls

Fire whirls–whirlwinds of fire–are one of the most spectacular fire behavior phenomena. They resemble the appearance and behavior of dust devils that often develop on strongly heated land surfaces. Fire whirls are common in wildland fires where they vary greatly in size, strength, and duration. Most whirls are small, but occasionally a large one of destructive size and force will develop. Air flow speeds in such whirls have not been accurately measured, but must be high. Type of damage is similar to that of tornadoes. In the Polo Fire near Santa Barbara in 1964 (Pirsko, Sergius, and Hickerson 1965), for example, a large whirl moved out of the fire, demolished two houses, damaged several others, and caused other damage. It uprooted large trees and slammed a piece of quarter-inch plywood 3 inches into an oak tree.

Fire whirls have also been reported in urban conflagrations. In the Tokyo fire after the 1923 earthquake, fire whirls were reported in several eyewitness accounts (Busch 1962). One large whirl in this disaster was apparently responsible for many casualties and extensive fire spread.

Tornado-like winds have also been reported in both urban and wildland fires. These winds seem to differ from the fire whirls in origin in that they appear to begin well above the ground surface, and then extend to the ground. Then their behavior becomes the same as for fire whirls.

Conditions for Development

The mechanism of the development of fire whirls in the open is far from being completely known. Research and observation, however, have provided some clues about the characteristics of fire whirls and where they may develop. Byram and Martin (1962) and Broido (1964) have used a special device to create a fire whirl on a minature scale. The device imparts a rotational motion to air flowing into a fire burning a small quantity of hydrocarbon. Greatly increased burning rates and flame heights were observed in these experiments. Theoretical treatments of fire whirls have also been attempted[4] but these hypotheses have not been tested under actual conditions.

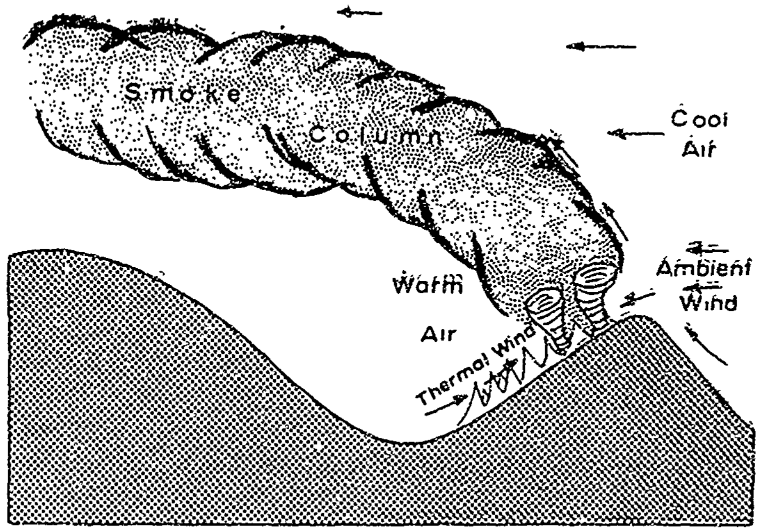
On wildland fires and prescribed burns, observers report that fire whirls appear most frequently on the lee side of a ridge. It has been suggested that the whirls may result from low pressure areas caused by flow across the ridge (Graham 1957). Fire whirls have been observed in fires over an area where an air flow eddy created by topography was known to exist (Countryman 1964). They have also been observed to occur more frequently when the air mass was unstable to a considerable depth-such as was the case in the Hamburg fire storm in World War II (Ebert 1963).

Fire whirls developed during some stage of the fire on all of the Flambeau tests. One fire was set up to meet as many of the known conditions required for fire whirl development as possible (Countryman 1964). The plot of 72,000 square feet was located on a lee slope within a small canyon. The plot was burned in late afternoon during unstable air conditions with a wind of 8 to 10 m.p.h. across the ridge top.

The upper half of the plot was fired first to create upslope thermal air flow, and the lower half fired 2 or

[4]Dergarabedian, Paul, and Fendell, Francis. *Parameters governing the generation of geophysical vortices.* (n.d.) (Unpublished office report on file TRW Systems, Redondo Beach, Calif. 19 p., illus.)

Figure 69—*Most fire whirls in the Flambeau tests developed on lee slopes. They resulted from an unstable condition in which thermal wind and the fire blocked incoming cool air.*



3 minutes later to provide additional heat. The fire built up rapidly, and fire whirls began to occur as soon as the initial fires began to merge. Whirls increased in size and frequency over time. The largest whirls, filled with dust and ashes, developed after practically all of the fuel bed had been consumed.

From a helicopter we could see that most of the whirls were developing along a line parallel to the ridge, and about 50 to 75 feet below the ridge top. From the smoke movement, it was obvious the whirls were forming near the point where the cool ambient air met the warm thermal winds from the fire—and where eddies could be expected to develop. The cool air was blocked by the fire and thermal winds, and tended to flow over the canyon. The result was an unstable condition *(fig. 69).*

On the other Flambeau tests on near-level terrain, most fire whirls tended to develop on the lee side of the fire. In Test Fire 5, for example, fire whirls developed repeatedly along the boundaries of the

Figure 70—*Paired fire whirls, developed in Test Fire 5, June 14, 1966, each rotating in opposite directions.*

strong inflow area on the lee side of the fire (fig. 44). Frequently two or more whirls on opposite sides of the inflow boundary and rotating in opposite directions appeared at the same time (fig. 70). The same situation developed in Test Fires 2 and 6.

The whirls developing in the Flambeau test fires were small - usually less than 10 feet in diameter. Occasionally a whirl would extend to 3,000 feet or more into the convection column. The flame height in the whirls, however, seldom exceeded 50 to 60 feet and usually was not more than 1.5 to 2 times the flame height of the burning fuel beds.

Hazards

In a rapidly spreading, wind-driven wildland fire, fire whirls are not critical - rarely do they contribute directly to spread while the fire is running. Under some situations, however, fire whirls may be one of the mechanisms for injecting firebrands into the convection column and may thus contribute to fire spotting. Once a control line is established around a fire the development of fire whirls assumes greater significance. Whirls developing within the fire area can and do pick up burning materials and scatter them outside the control line, thus starting fire spread anew. This occurs often enough to be a problem in fire control in wildlands. In urban fires, spread of such fires is generally slow, fuel loading is heavy, burning time relatively long, and channeling of air flow in streets and between buildings prevalent. Under these conditions large, intensely burning areas are likely to develop, fostering the creation of fire whirls. The capability of whirls to produce fire brands can help spread fire.

Fire whirls in urban fires may be hazardous to the civilian population, including firefighters, and are potentially dangerous to buildings and equipment. These hazards exist within and outside the fire boundaries. The hazard to human life comes not only from the rapid spread of fire by the whirls, but also from the strong possibility that whirls contain large amounts of noxious gases or at least are deficient in oxygen whether they contain fire or not.

Accounts of the whirls in the Tokyo fire of 1923 (Busch 1962) mention that people had difficulty breathing when the whirls passed over (without fire). Firefighters in wildland fires have also related the "lack of air" when caught even in small whirls that have moved out of the fire area. It is also likely that the pressure within the whirls is low. A whirl passing over an unsealed shelter ventilation system can reduce the pressure within the shelter. If the whirl is followed by flames at near ambient pressure, as they very likely would be, the noxious gases present in the flames could be drawn into the shelter at high temperatures with disastrous results to the occupants.

Although the mechanisms of fire whirl development are not well understood, there are certain areas and conditions that are conducive to their appearance. One of the more important of these conditions is the presence of vorticity in the air flow in or around the fire area. This is evidenced by the fact that the whirls occur most frequently where eddies in the air flow are most likely to occur, such as on the downwind portions of the fire area, on the lee side of ridges, or certain topographic configurations. Fire appears to concentrate and intensify the vorticity already present in these areas.

Vortices also seem to occur more often under a strongly leaning convection column than a more erect one. With leaning columns the vortices appear as fire whirls in the fire area, and as dust devils downwind from the fire. Whether the more frequent occurrence of vortices under this condition is caused by unstable conditions created by cool ambient air over the warm column, to the air circulation pattern set up by the column itself, to more wake eddies from the stronger air flow needed to make a convection column lean, or to a combination of all of these factors is uncertain. It is obvious, however, that fire whirls are a common fire behavior phenomenon. The likelihood of very large fire whirls or vortices developing in mass fires does not appear to be great. More research, both theoretical and experimental, is needed before the significance of fire whirls to mass fire behavior is firmly established.

CHARACTERISTICS OF MASS FIRE

The primary purpose of Project Flambeau was to gain enough information about large fire behavior to permit writing a prescription for fuels and weather that would produce a mass fire. Unfortunately, there has been no clearcut definition of mass fire.

The term "mass fire" was coined shortly after World War II when it became obvious that the large, destructive fires created during that war would undoubtedly occur in any further large-scale military action—particularly with the advance of weapons

technology and its great fire-setting potential. Since the term "mass fire" was not clearly defined it has come to have various shades of meanings, depending upon the experience with fire an individual might have and the purpose for which he applied the term.

It would be presumptuous to claim that with the few fires completed in the planned Flambeau program, and these under a limited range of fuel and environmental conditions, that enough knowledge was gained to permit an unequivocable definition of mass fire. However, the Flambeau test fires provide the most complete, and indeed, perhaps the only quantitative data that make a beginning in the delimitation of mass fire possible.

Just where on the scale of fire behavior a fire becomes a mass fire is uncertain. In natural wildland fuels, fires may burn in grass or leaves with flames only a few inches high. In other situations dense brush or timber stands will burn with flames 200 feet or more in height. Combustion rates also vary widely in urban fires–depending on size of building, construction material, building contents, ignition pattern, and other factors.

Fires large in area are not necessarily mass fires, since low energy release rates do not usually generate violent fire behavior. And the behavior of a small sector of such a fire is little different than if that sector was burning alone. On the other hand, very small fires burning with a high rate of energy release seldom exhibit violent fire characteristics. The term "mass fire" then carries the connotation of both large size and high rates of energy release.

Since energy release rates and fire area are both on continuous scales the problem of defining mass fire then resolves into setting threshold values on these scales where a fire can be considered a mass fire. A general definition of these values is: The minimum fire area and energy release rate at which a further increase in fire area or energy release rate will not significantly change the pattern of fire behavior. The chief concern in the definition is the pattern of behavior. Greater fire area or energy production may change the magnitude or violence of the fire phenomena produced, but the general pattern of these phenomena should remain unchanged.

Energy Production Threshold

In the Flambeau test fires, those fires with apparently the greatest energy release rates were characterized by tall flames in relation to the fuel bed height and by great turbulence in the combustion zone. Massive gas production was obvious, with ring vortices composed of flame and large and boiling masses of flame common. This type of fire did not usually appear or continue unless the energy production rate was 8,000 Btu/ft.^{2}/min. or more. Fire activity decreased as energy production rate decreased, and the violent activity largely disappeared below 5,000 Btu/ft.^{2}/min. Thus an energy production rate threshold of 5,000 to 8,000 Btu/ft.^{2}/min. would seem reasonable for the appearance of mass fire.

Fire Area Threshold

The area of fire at which the minimum energy release rate will produce a mass fire is more difficult to delimit. Other factors than sheer size are involved, such as wind speed and fuel bed configuration. Area of fire needed to produce mass fire characteristics also appears interdependent on energy release rate.

A characteristic of large fires is their tendency to break up into numerous small convection columns within the combustion and transition zones. This characteristic has been observed in wildland fires as well as on the more ordered fuel beds of the test fires. The tendency for fires over some critical size to burn and behave as a complex of many smaller fires provides a useful criteria in distinguishing mass fires from small or low-intensity fires.

Another characteristic of the close-spaced multiple-fuel-bed fires was the dominance of the fire in controlling the circulation pattern within the fire area. This same dominance of the fire in controlling the circulation pattern appeared in the larger single-fuel bed fires, although in these fires the individual convection columns drifted about, and the air flow pattern was more random in nature.

The tendency for multiple columns and internal air circulation patterns to develop, appeared frequently in single-fuel fires of the standard size (2,200 sq. ft.). Some indication of the same behavior was apparent in milled-fuel cribs as small as 144 sq. ft. in area. However, in these fires the ambient air flow appeared to play a dominant role in the circulation pattern. The only single-fuel-bed fire (380-6) in which the fire began to control the internal air flow pattern was about 50,000 sq. ft. in area. The ambient air flow during this fire was approximately 10 ft./sec. Energy rate production is not available but likely exceeded 5,000 Btu/ ft.^{2}/min. for much of its active period, and over 8,000 Btu/ft.^{2}/min. in the early stages. We estimated that the fire should have been at least 100,000 sq. ft. in area or greater to have fully exhibited mass fire characteristics.

Probability of mass fire developing is determined

in part by how the fuel beds are spaced. For a given size of fuel bed and level of heat energy production per unit area of fuel bed, increasing the spacing must obviously reduce the average energy yield for the fire area as a whole. However, from the Flambeau tests it appears that as long as the fuel bed spacing is not too great, mass fire characteristics associated with fire area will persist as long as the energy production rate of individual fuel beds exceeds the minimum level for mass fires.

Just where spacing distance becomes critical is uncertain. For the Flambeau fuel beds the spacing of 25 feet produced mass fires for part of the burning span in all tests. The ratio of fuel covered to total area for these fires was about 50 percent. In the wide-spaced plots this ratio was only about 15 percent, and mass fires were not produced although the individual fuel bed energy rate may have exceeded 10,000 to 12,000 Btu/ft.^{2}/min. But conceivably larger fires with this wider spacing might have produced mass fires. Since the maximum size of wide-spaced fuel-bed fire was only 137,000 sq. ft., the effect of fuel bed spacing on mass fire development is left unanswered.

The smallest close-spaced fuel-bed fire (Test Fire 2, burned May 15, 1964), covered about 165,000 sq. ft. Although energy rates were not measured directly, estimates based on the appearance of burning fuel beds where the energy rate was known indicated the rates well above the minimum threshold for mass fire. Circulation patterns were almost completely dominated by the fire within the fire boundaries. Apparently a smaller fire of this configuration would also have produced mass fire characteristics. It thus seems reasonable to conclude that the minimum size fire to produce a mass fire in multiple-fuel-bed fires is in the order of 100,000 to 150,000 sq. ft., with a uniform fuel coverage pattern over at least 50 percent of the fire area. And ambient wind speed should not exceed 10 ft./sec. These same requirements apply to single-fuel-bed fires.

With these specifications the mass fire would have massive, turbulent flames, with multiple convection columns in the combustion and transition zones. Thermal energy output would exceed 5,000 Btu/ft.^{2}/min., and the fire would dominate circulation patterns within the fire area. The fire area would be at least 100,000 square feet, with 50 percent of the area covered with fuel beds in a uniform pattern. And ambient wind would be less than 10 ft./sec.

Specifications for Mass Fire

Fuel element and fuel bed characteristics largely determine the kind of fire that is produced. Results from the mass loss experiment in Test Fire 6 indicated that for multiple-fuel bed fires, the location of the fuel bed within the fire area only slightly affected the energy production rate. Thus a single-fuel bed designed to yield the necessary rate of thermal energy will produce a mass fire when enough of these fuel beds are burned in a uniform array.

The milled-fuel beds used in the mass loss experiment, if burned singly when the fuels are dry, will give a peak energy rate of about 17,000 Btu/ft.^{2}/min. and an energy rate greater than the 5,000 Btu/ft.^{2}/min. minimum set for mass fire for about 11 minutes. The strong air flow and turbulence within a mass fire would tend to reduce this peak somewhat and extend the time the energy rate is over the minimum. Therefore, fuel beds of this configuration are suitable for creating mass fire

The following specifications for fuel bed design, fire configuration, and weather that will produce a mass fire are based on Flambeau tests. There are, of course, many other fuel bed designs and fire configurations possible that will also produce mass fires.

Fuel Bed (Wood Fuel):	Specifications for a mass fire:
Surface to Volume Ratio (σ)	25.11 ft.^{2}/ft.^{3}
Porosity (γ)	23.85 x 10^{-2} ft.^{3}/ft.^{2}
Fuel Loading	>17 lbs./ft.^{2}
Kindling Fuel	10 x 10^{-2} lbs./ft.^{3}
Fuel Bed Area	>1700 ft.^{2}
Ignition Points	1/300 ft.^{2} of fuel bed area
Fuel Moisture	<10 percent
Fire:	
Fire Area	>100,000 ft.^{2}
Fuel Bed Spacing	<25 ft.
Terrain	Level (Approx.)
Weather:	
Ambient Wind 10 ft. level	<10 ft./sec.
Ambient Wind 5000 ft. level	<20 ft./sec.
Relative Humidity	<30 percent
Temperature	>50° F.
Lapse Rate	Neutral to unstable

SUMMARY AND CONCLUSIONS

Project Flambeau was an exploratory study into mass fire behavior. Its principal purposes were to provide descriptive information on large fire systems and to develop instrumentation systems and techniques suitable and adequate for full-scale mass fire studies. Data collected were not primarily for the purpose of developing statistically valid cause-and-effect relationships. Rather the intent was to obtain data which could provide the foundation for development of realistic theory concerning fire behavior and to provide guides to the development of experimental studies, both in the field and in the laboratory, that could be aimed at the solution of fire problems with a reasonable expectation of deriving practical results. These objectives have largely been accomplished

Flambeau test fires have been few, and have been burned under a limited range of fuel and environmental conditions. Data from these tests have yet to undergo rigorous analysis. Nevertheless, it is possible to draw some of the more obvious conclusions from the completed tests:

1. *Fuel characteristics, including those associated with both fuel elements and fuel beds, are the major controlling factors in fire behavior.*

The burning fuel provides the basic driving energy for fire behavior phenomena associated with fire. How the potential thermal energy of the fuel is released may be affected in some cases by such environmental conditions as wind speed and air stability. In general, however, the thermal pulse produced by a given fuel bed will depend largely on the characteristics of the fuel and of the fuel bed itself.

2. *Rate of thermal energy production is of primary importance in determining fire characteristics and behavior.*

The rate at which the thermal energy of fuel susceptible to combustion is produced is far more important than the size of the burning area. Close-spaced fuel-bed fires in the Flambeau program varied in size by a factor of 11. However, air flow patterns, temperature, fire behavior, and noxious gas production were in general the same in the smallest as in the largest fires. The lower limit of fire size in which mass fire characteristics will appear was not determined with certainty. Because of the major influence of fuel characteristics this limit probably varies with fuel type. In fuels such as were used in Flambeau test fires, mass fire characteristics can be developed in fires in the order of 100,000 to 150,000 square feet in area. Test results strongly suggest that mass fires can be developed in a smaller area.

3. *Strong airflow and turbulence develop within the fire boundaries.*

In all test fires burned, the strongest air flow and turbulence were inside the fire boundaries away from major influence of ambient flow. In the multiple-fuel-bed fires the increase in air flow into the fire area was significantly greater than that of ambient flow. Air speeds within the fire area, however, were several times greater than the air inflow at the fire periphery.

4. *Radiation is of minor importance in fire spread outside of the fire boundaries.*

The lack of ignition by radiation outside of the fire boundaries was a marked characteristic of all Flambeau fires in this test series. Radiation as a factor in fire spread can be expected to become important only where spread by flame contact and firebrands is limited. For urban fires, of the type to be expected following nuclear attack, fire-induced turbulence within the area initially ignited will insure maximum flame contact and firebrand movement.

5. *For multiple-fuel-bed fires the position of a fuel bed in the array has only a minor effect on its thermal pulse pattern.*

In the mass loss experiment of Test Fire 6 only small differences were found in the mass loss rates for fuel beds in different positions. The differences that did appear seemed more closely related to variation in the circulation pattern within the fire area than to position of the fuel bed with respect to the fire center.

6. *The Countryman descriptive model is a realistic portrayal of a stationary mass fire system.*

All six zones of the model appeared in two of the test fires. I other tests the convection column di' not reach heights that permitted smoke fallout a:.d convective development zones to develop. Fire behavior and associated phenomena were generally similar in the fuel, combustion, and transition zones for all fires that produced mass fire characteristics.

7. *Wildland fuels may be used to simulate urban fires.*

Wildland and urban fuel beds are dissimilar and cannot usually be expected to produce similar fires in their natural state. But the thermal pulse produced by a burning fuel bed is dependent so much on fuel bed characteristics that it is possible to select and arrange wildland fuels to produce a thermal pulse that will be similar to that of an urban fuel, and to produce similar fire characteristics Success in simulation will depend upon knowledge of burning characteristics of wildland fuels and thermal pulse characteristics of the urban fuel bed to be simulated.

8 *Fire whirls are a consistent phenomenon in large and intensely burning fires.*

Fire whirls occurred in nearly all Flambeau test fires, and commonly occur in wildland fires. This phenomenon is of considerable importance in urban mass fire spread and in fire control activity. Fire whirls are likely to be of major importance in civil defense aspects of mass fire because of their destructiveness and their capability to rapidly spread fire and transport noxious gases.

9. *Lethal concentrations of noxious gases occur within and adjacent to fires.*

High concentrations of carbon monoxide, carbon dioxide, and deficiency of oxygen were found in the combustion zone of Flambeau fires. Less severe concentrations appeared between the fires and on the fire edge. Since peak concentration of lethal gases, minimum oxygen, and peak heat occurred at about the same time, their combined effect may be greater than any one alone. Also of significance is the long time duration of carbon monoxide concentrations within the fire area that are high enough to affect a person's judgment and action, although not directly causing permanent injury or death.

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